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(54) **SYSTEM AND METHOD FOR HIGH PRECISION MULTI-APERTURE SPECTRAL IMAGING**

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(58) **Field of Classification Search**

None

See application file for complete search history.

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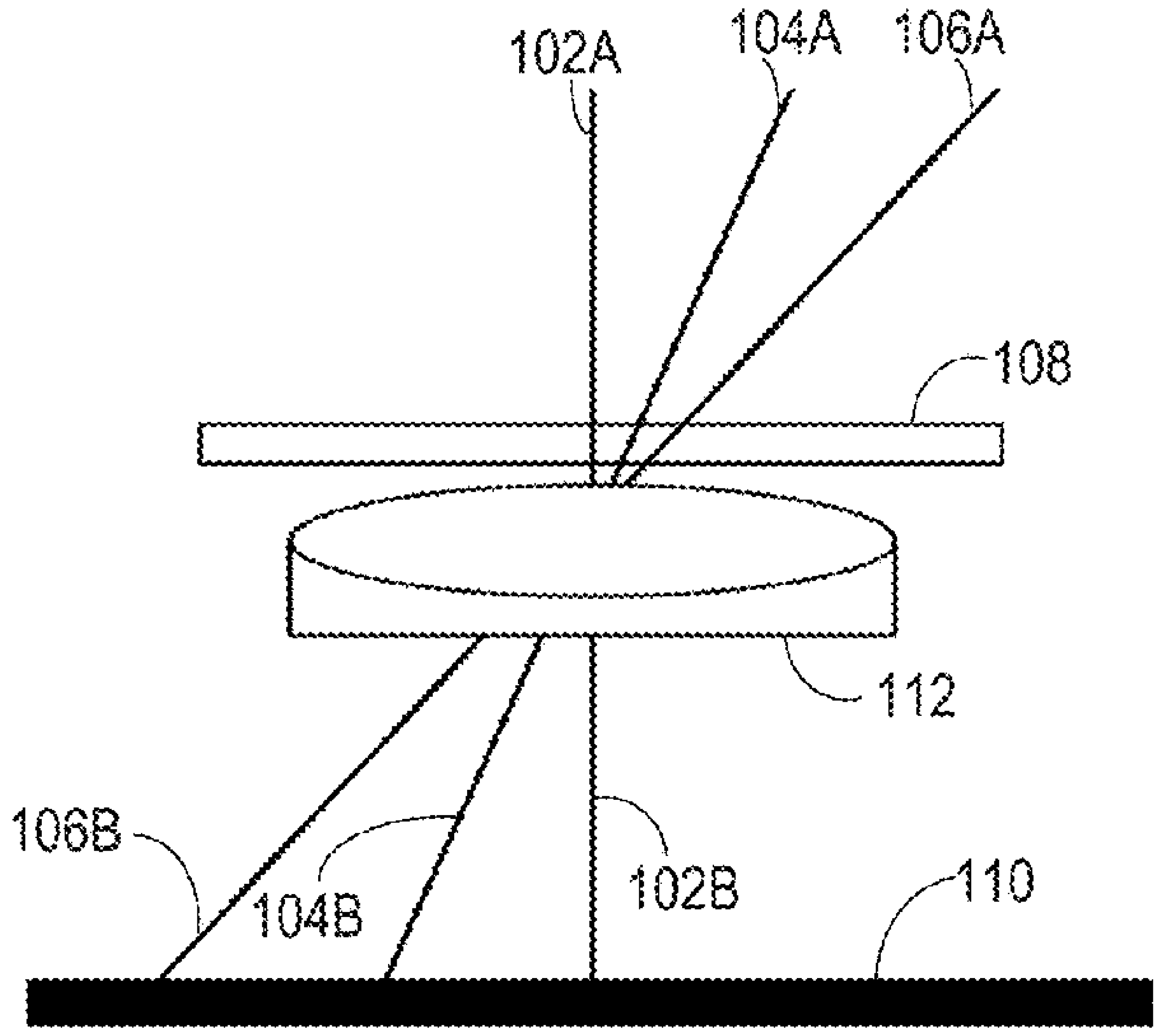
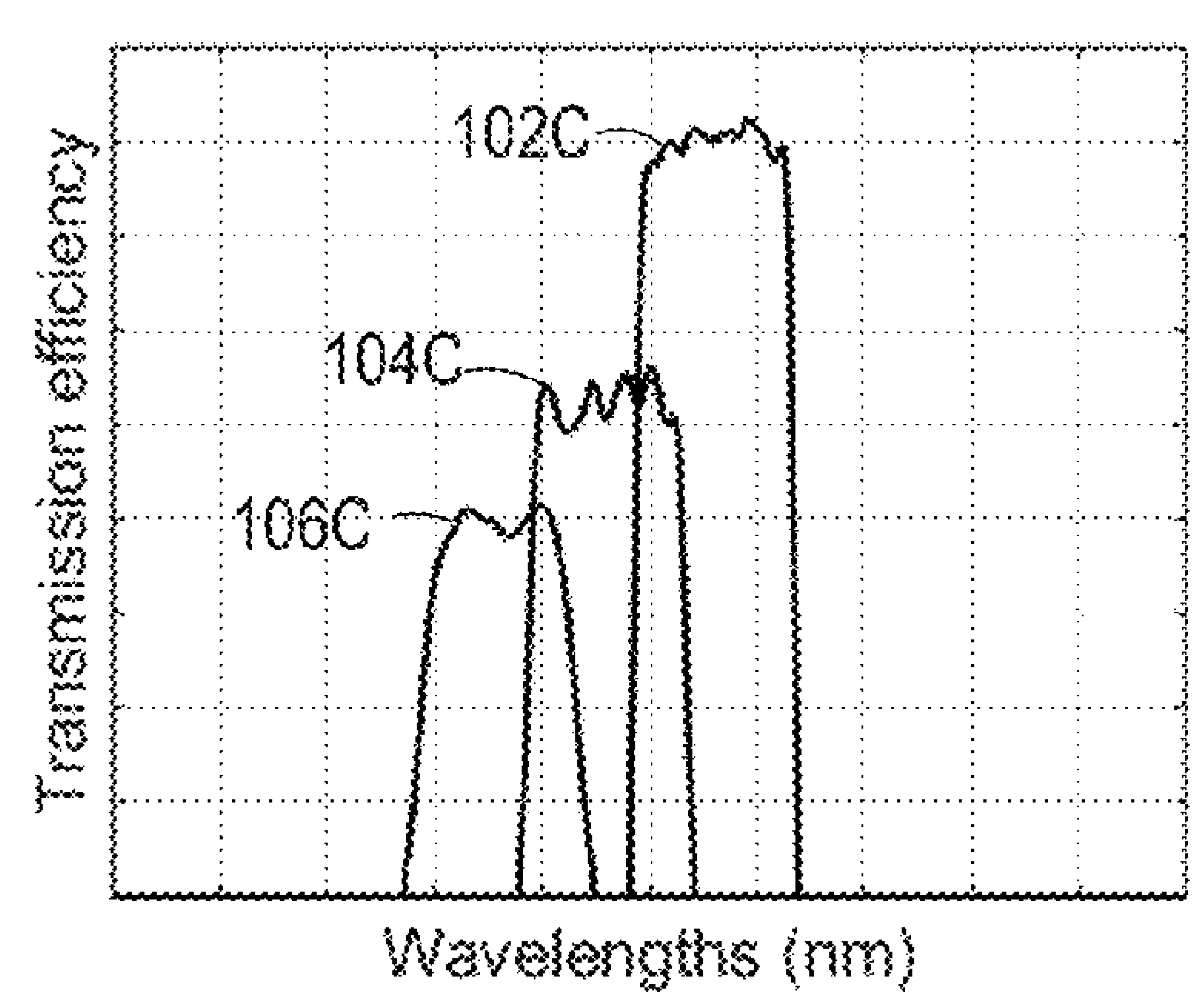
(57) **ABSTRACT**

Generally described, one or more aspects of the present application correspond to systems and techniques for spectral imaging using a multi-aperture system with curved multi-bandpass filters positioned over each aperture. The present disclosure further relates to techniques for implementing spectral unmixing and image registration to generate a spectral datacube using image information received from such imaging systems. Aspects of the present disclosure relate to using such a datacube to analyze the imaged object, for example to analyze tissue in a clinical setting, perform biometric recognition, or perform materials analysis.

20 Claims, 29 Drawing Sheets





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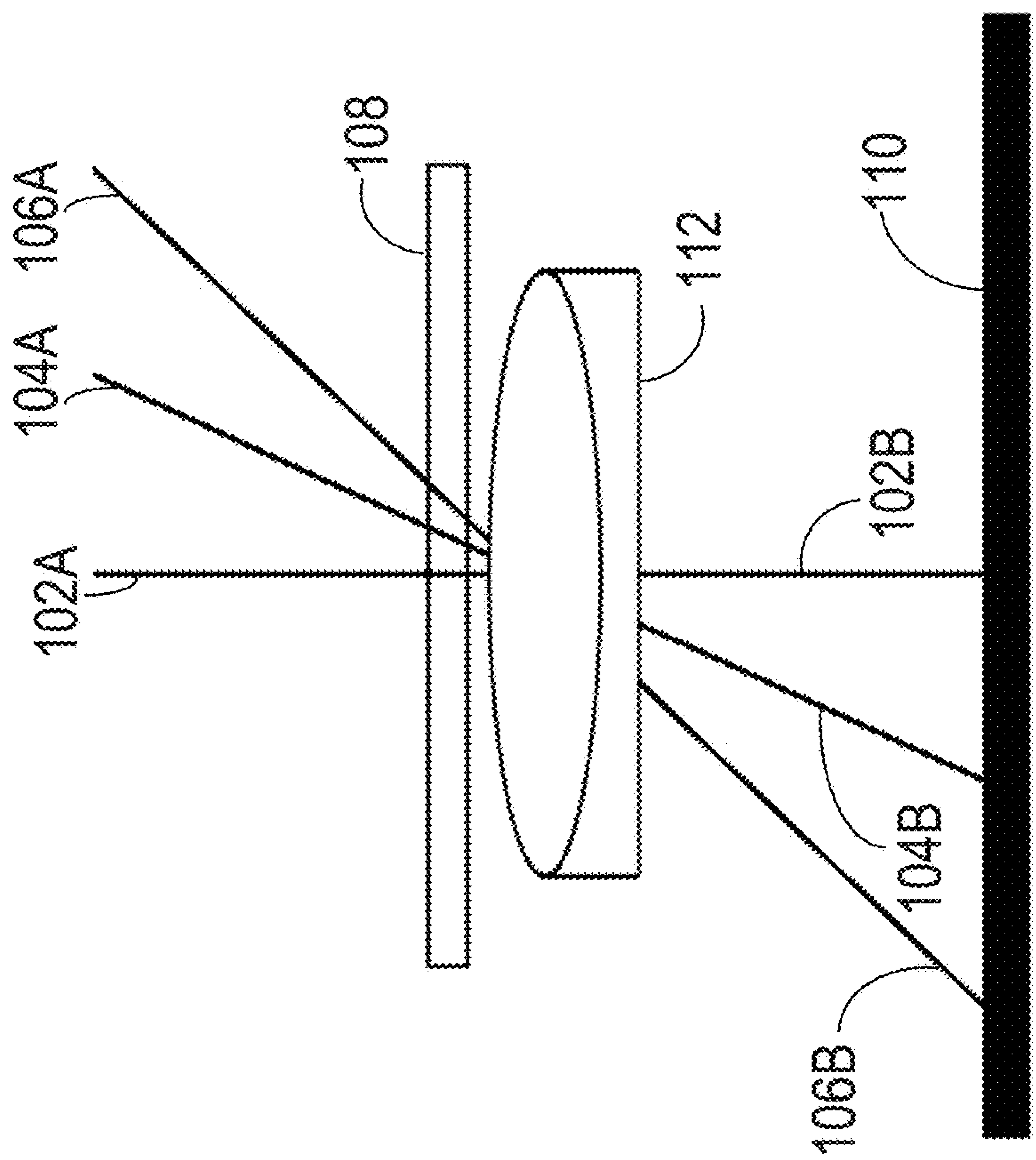
102A
104A
106A
108
112
110
102B
104B
106B

FIG. 1A

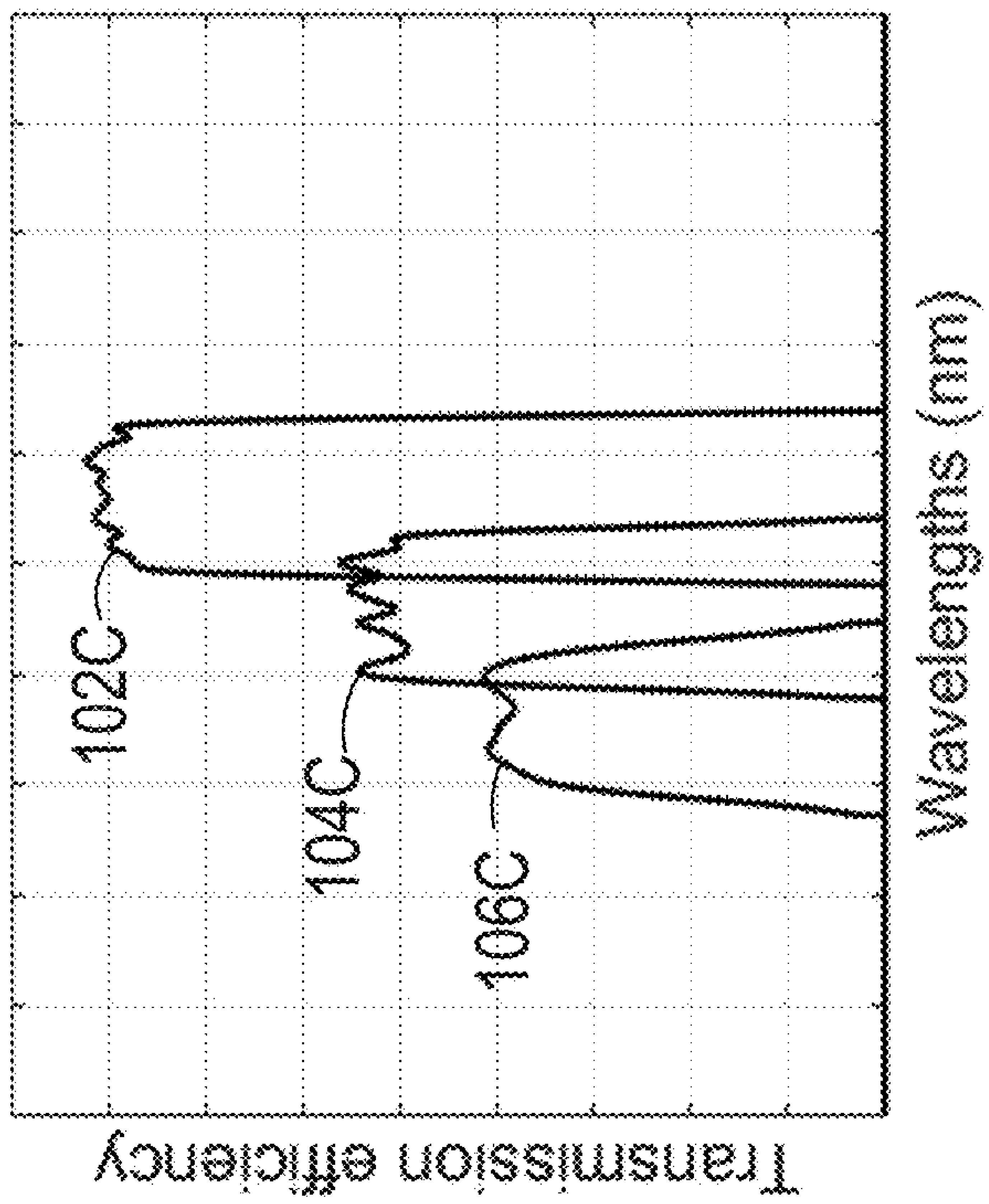
Transmission efficiency
Wavelengths (nm)
102C
104C
106C

FIG. 1B

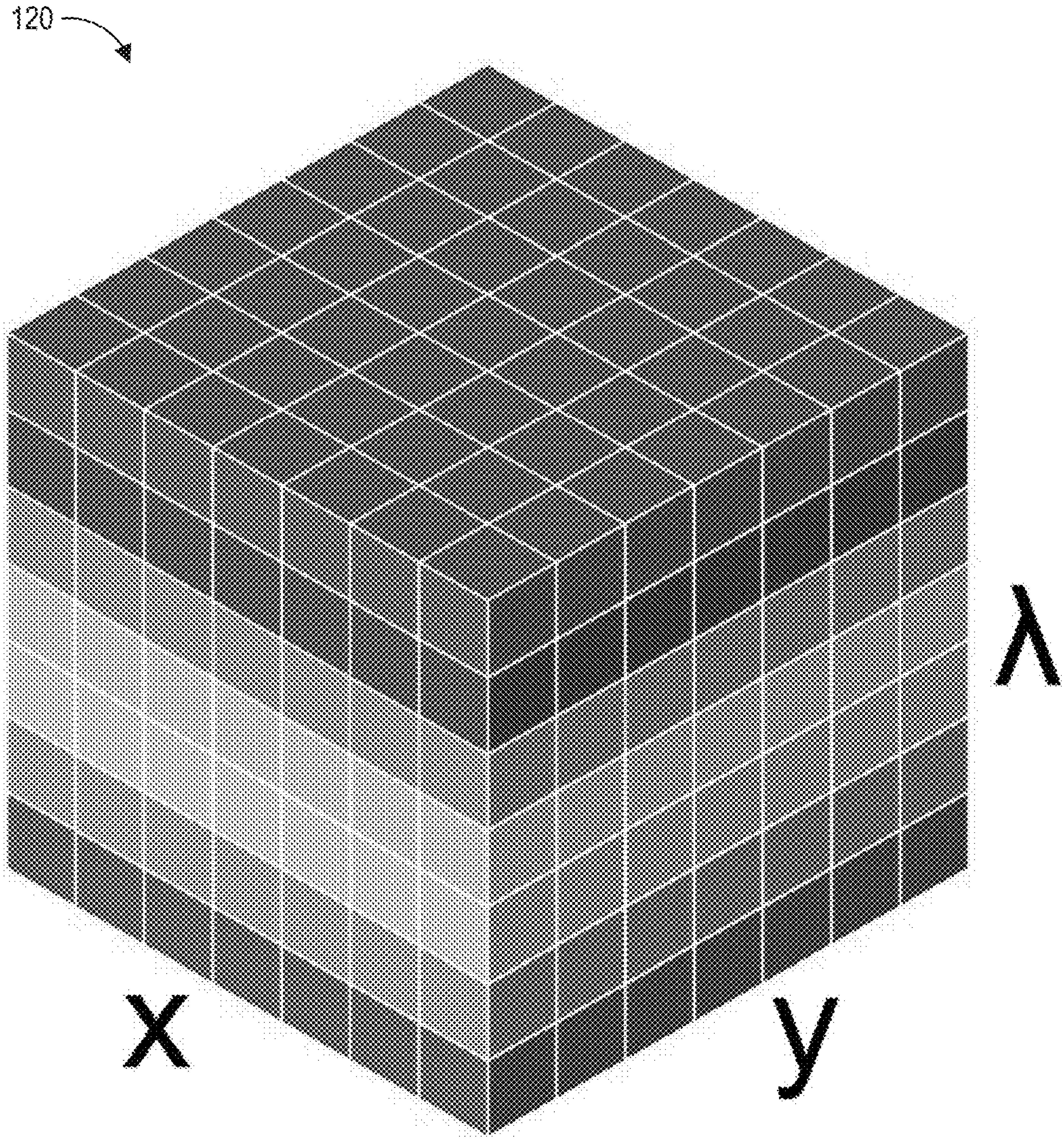

FIG. 2A

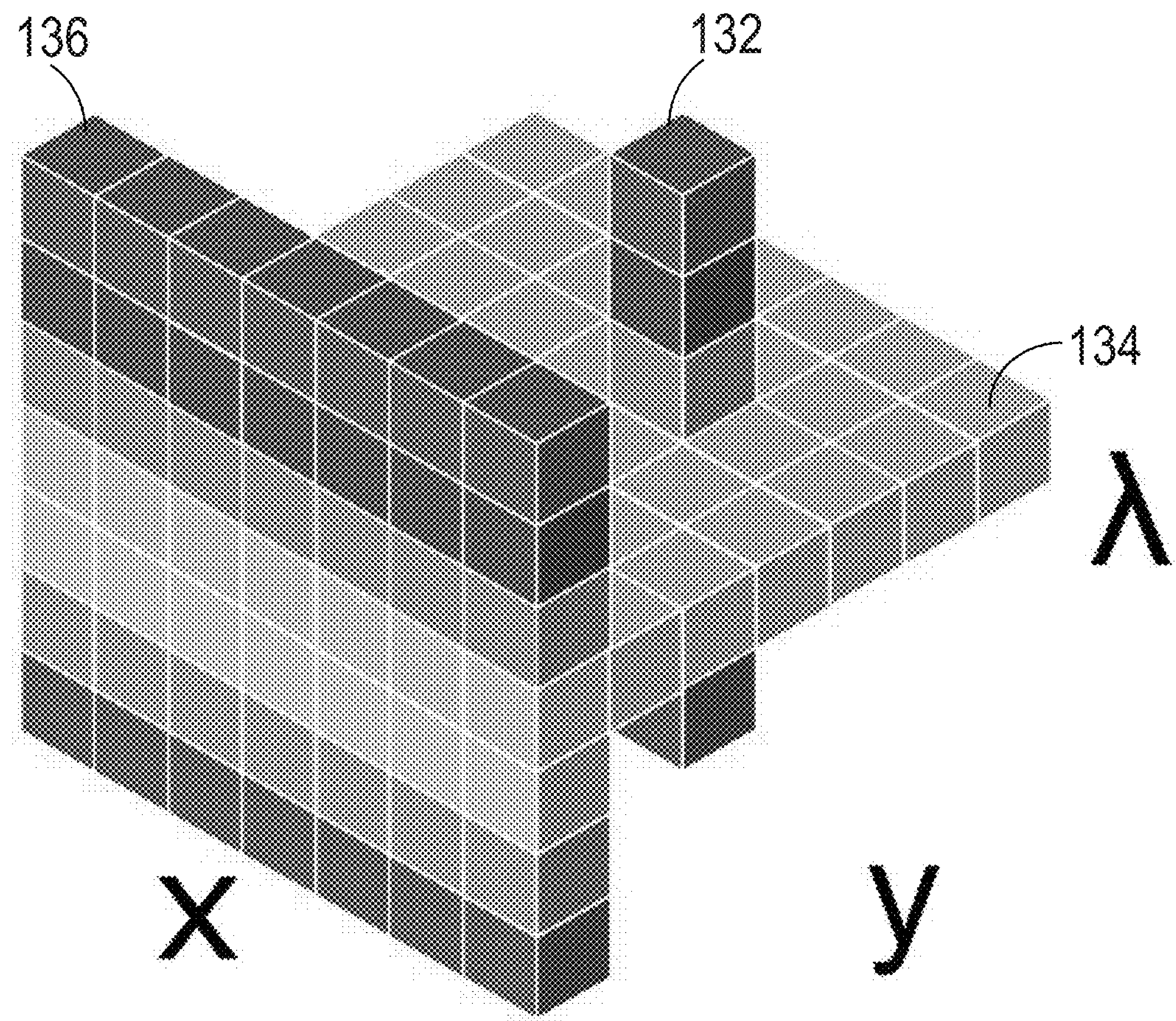

FIG. 2B

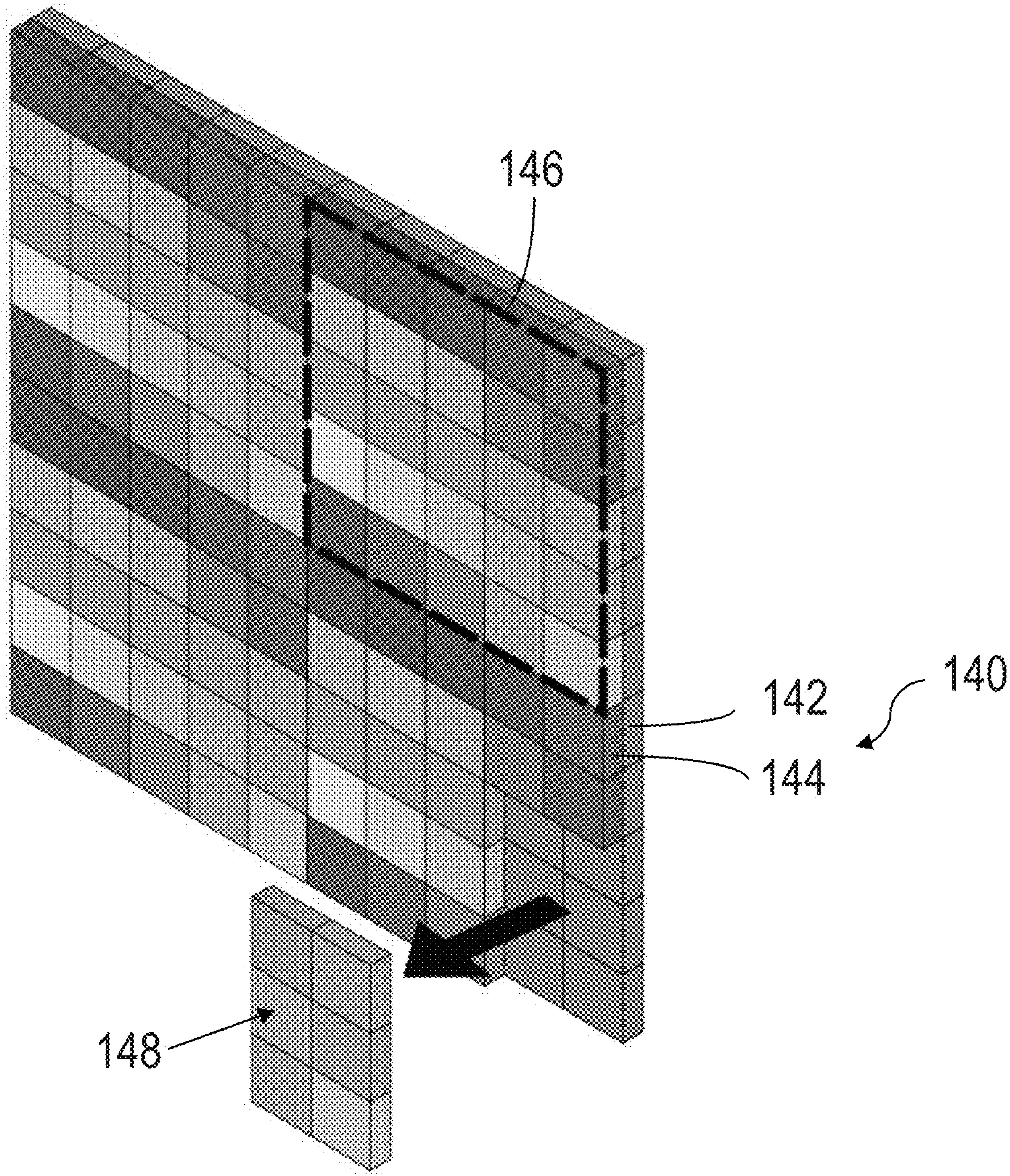

FIG. 2C

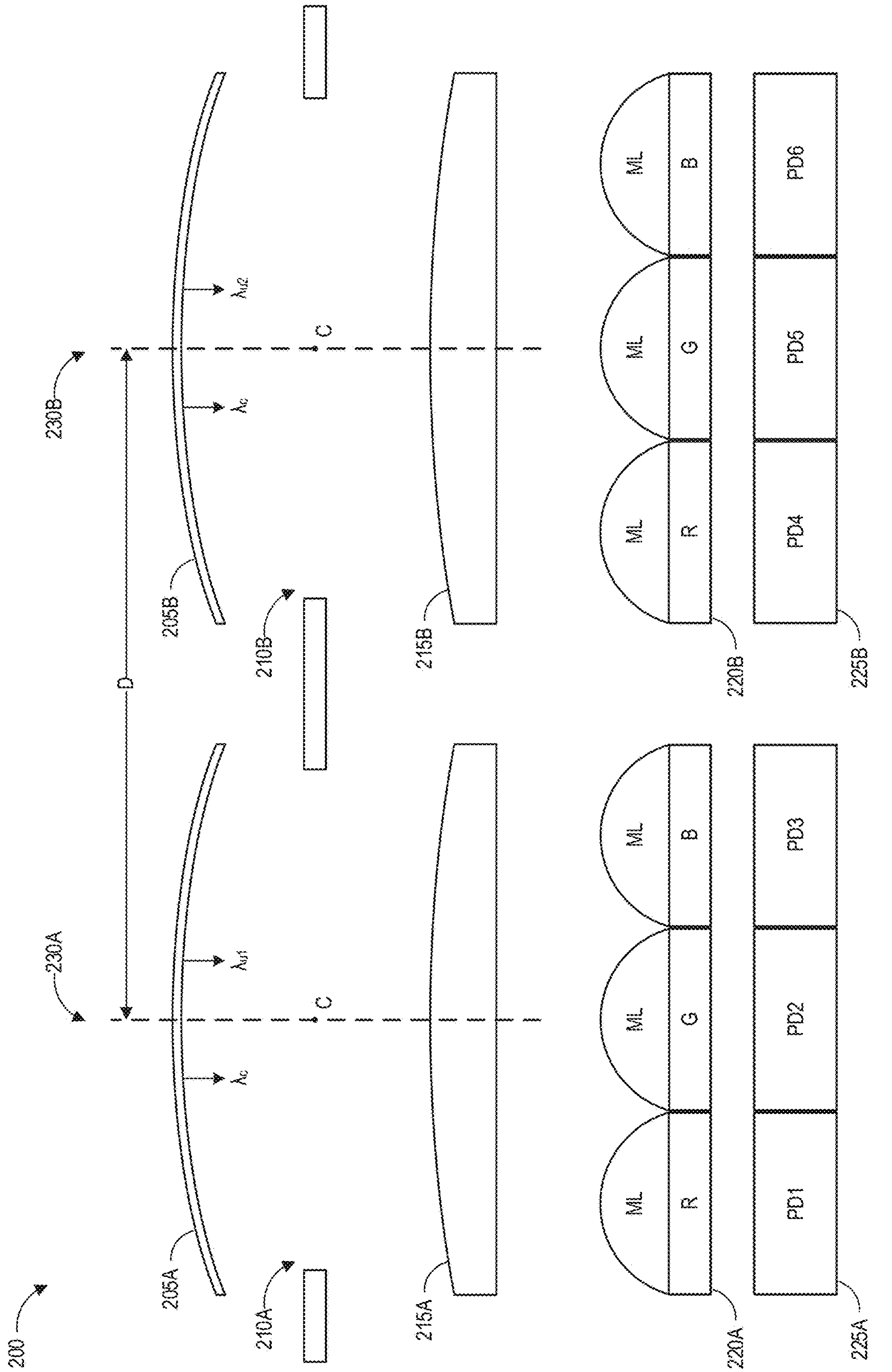
200
205A
205B
210A
210B
215A
215B
220A
220B
225A
225B
230A
230B
D
C
C
λ_c
λ_{d1}
λ_c
λ_{d2}
ML
ML
ML
ML
ML
ML
R
G
B
R
G
B
PD1
PD2
PD3
PD4
PD5
PD6

FIG. 3A

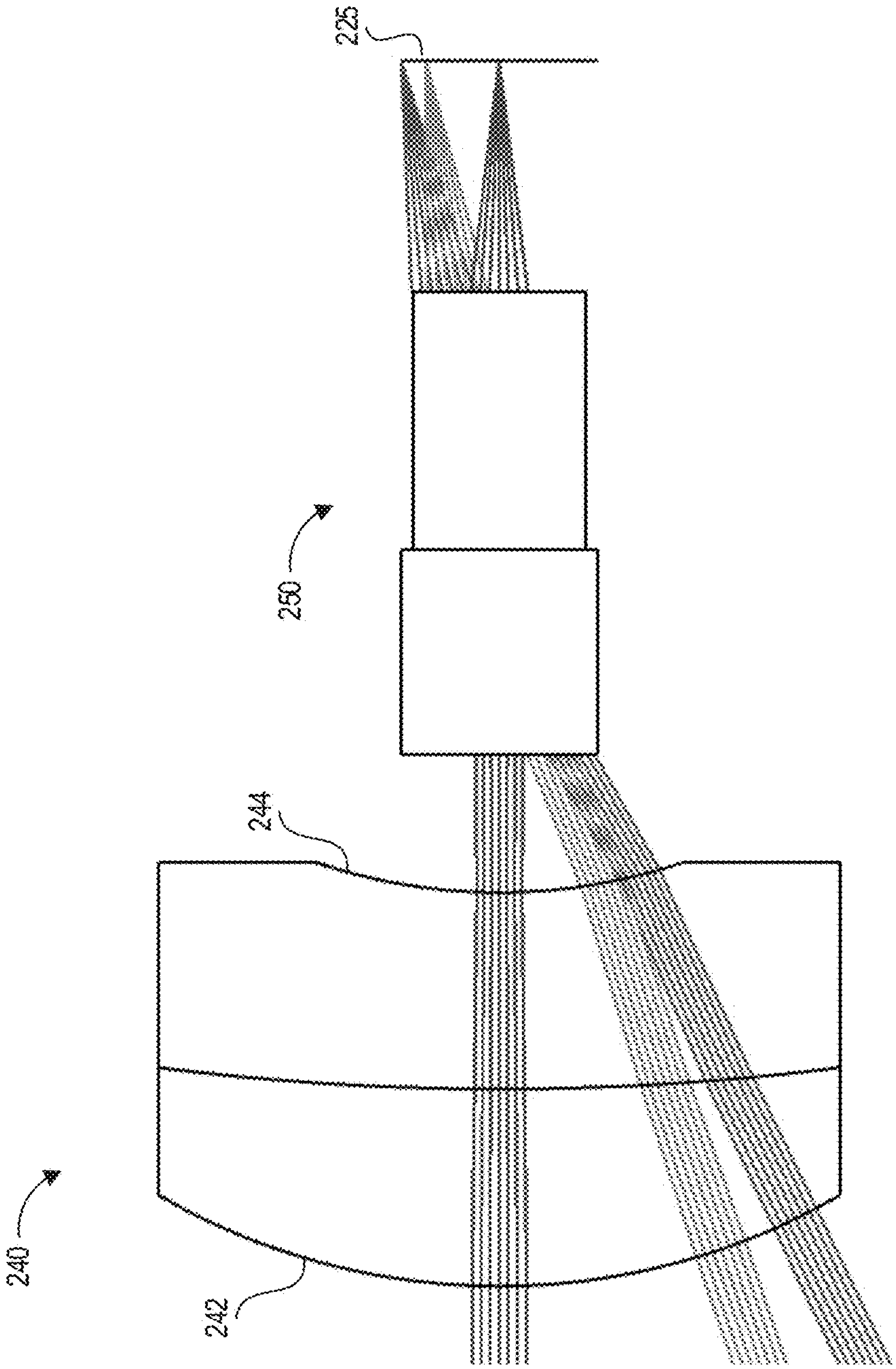

FIG. 3B

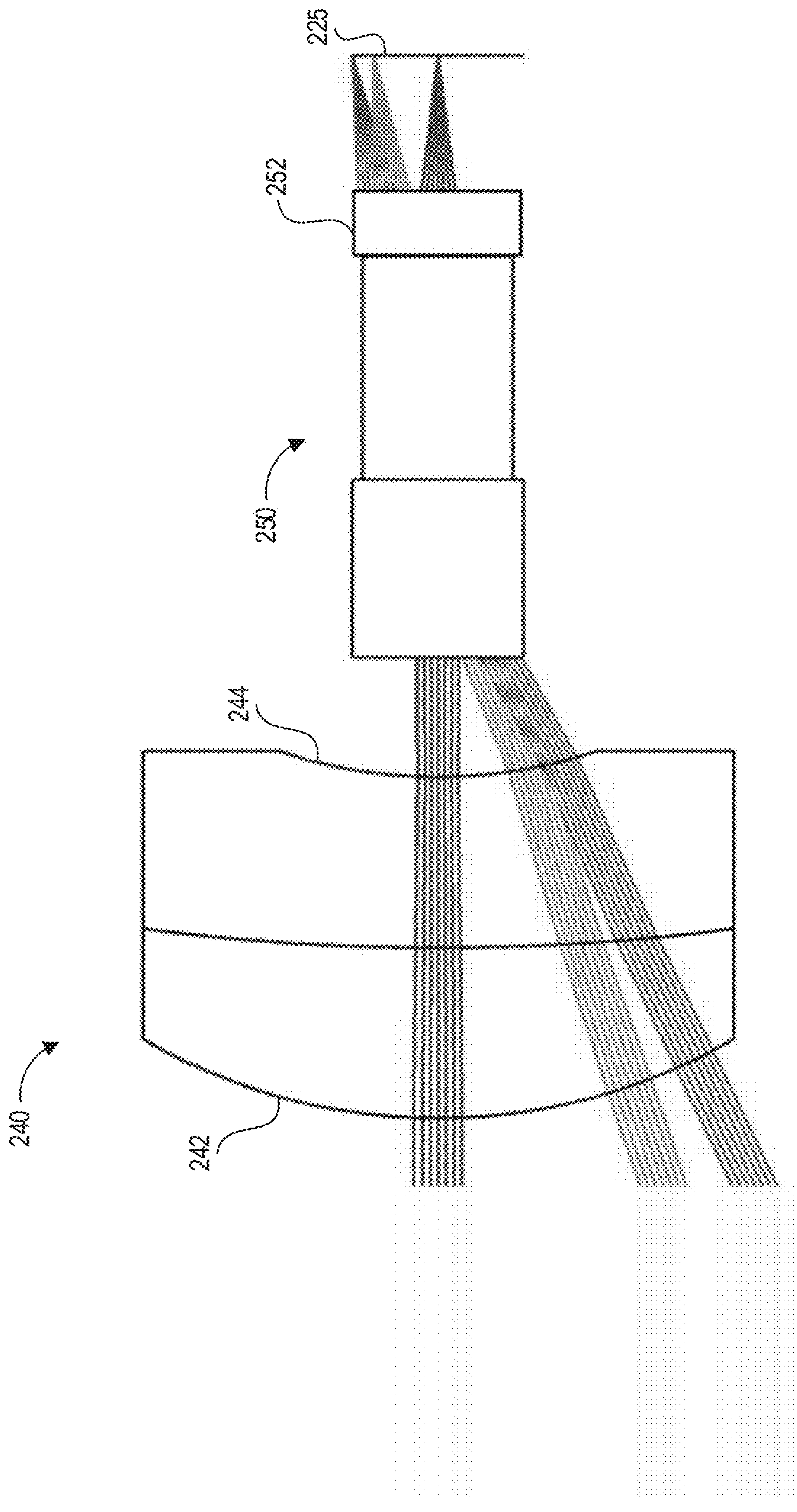

FIG. 3C

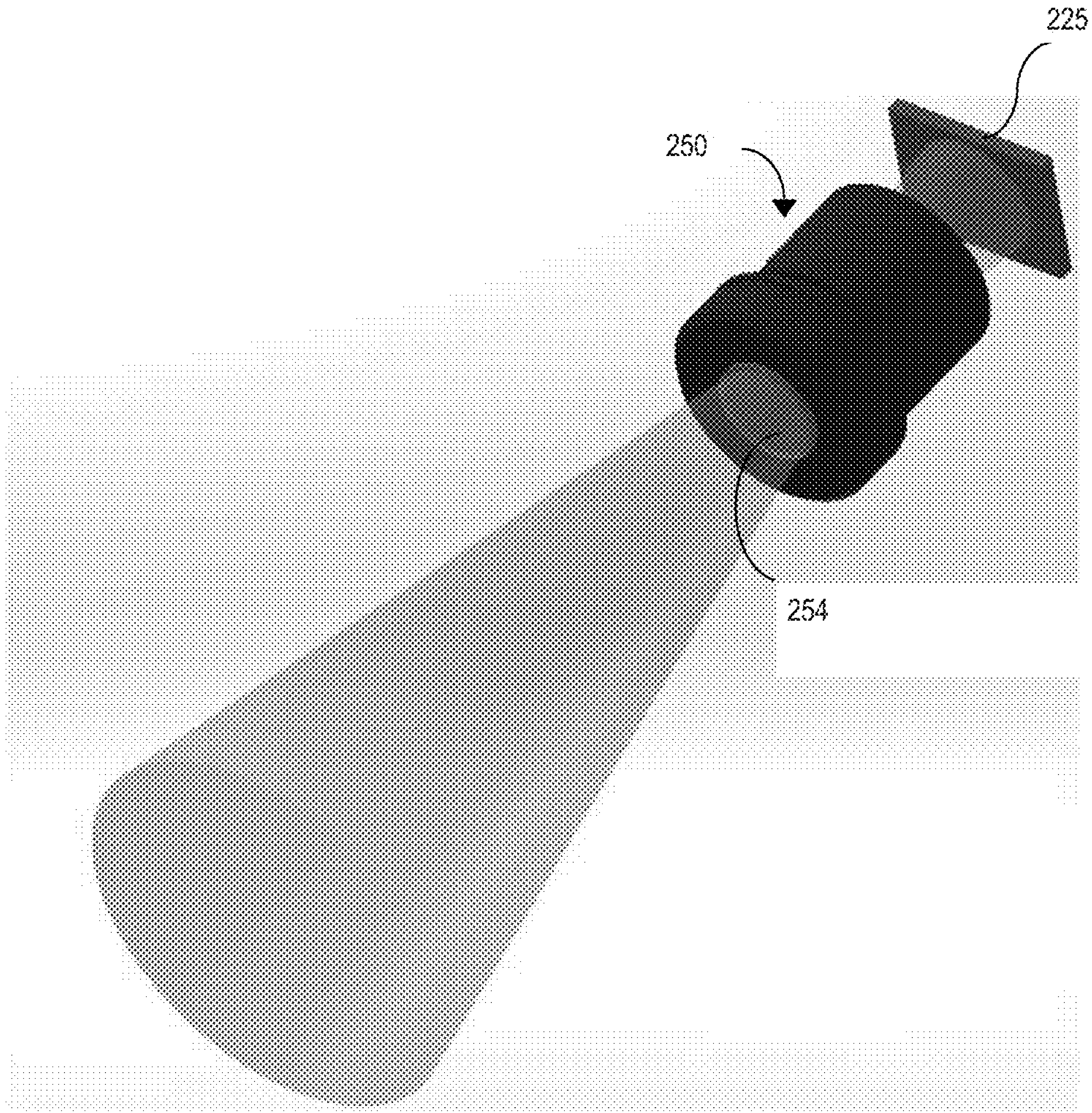

FIG. 3D

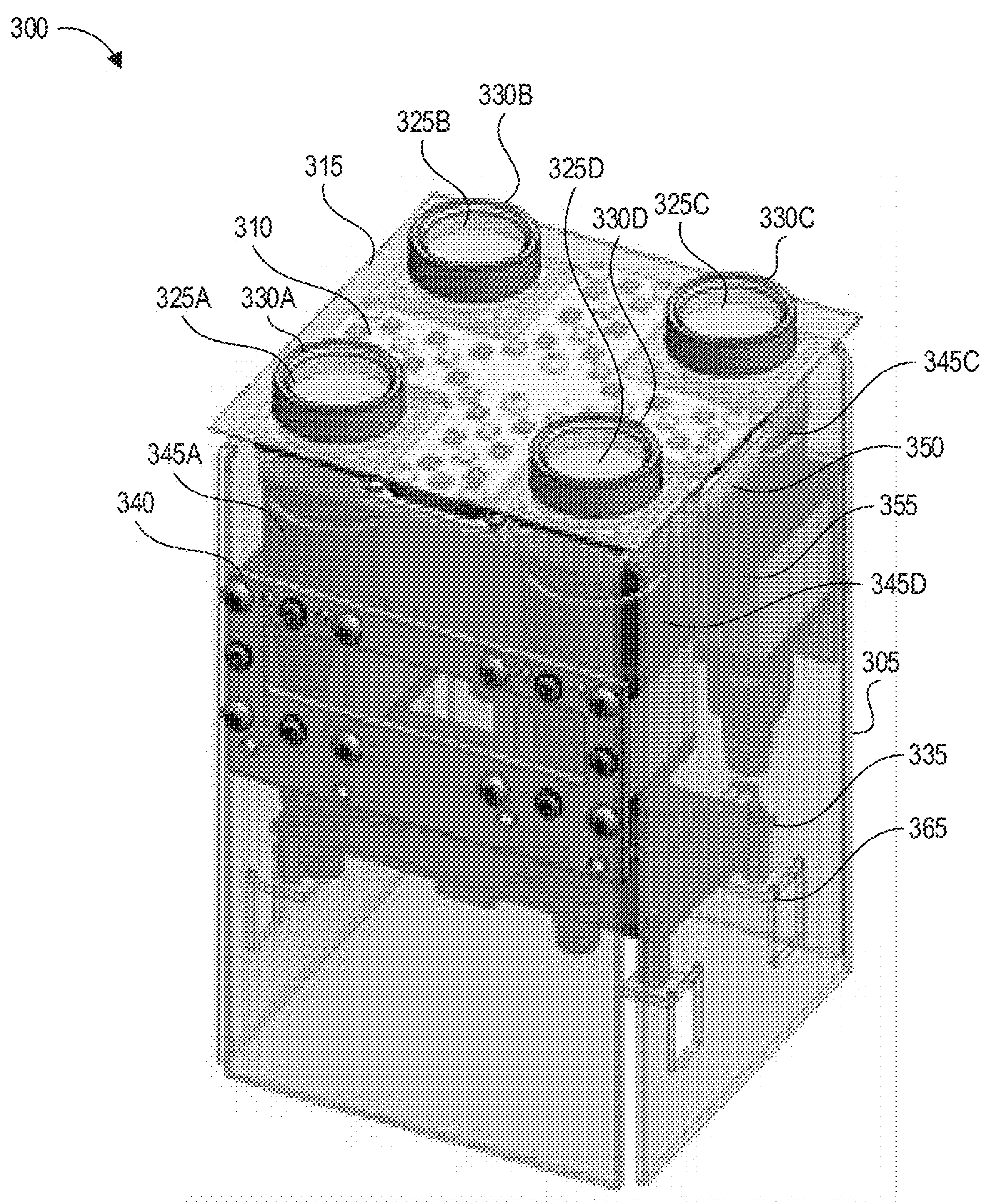
300
325B
330B
315
325D
310
330D
325C
330C
325A
330A
345C
350
345A
355
340
345D
305
335
365

FIG. 4A

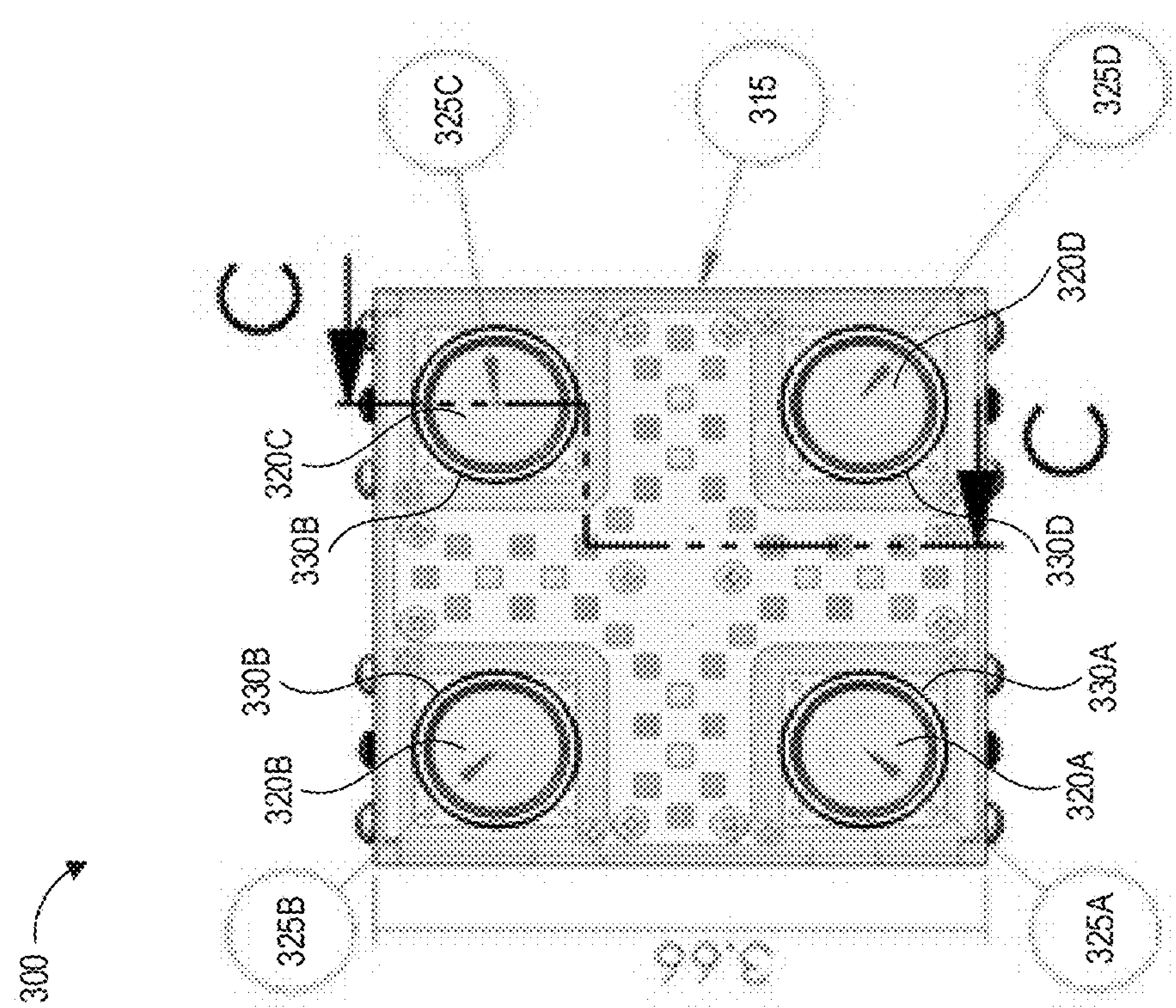
300
325B
320B
330B
320C
330B
C
C
325C
315
325D
320D
330D
330A
320A
325A
3.66

FIG. 4B

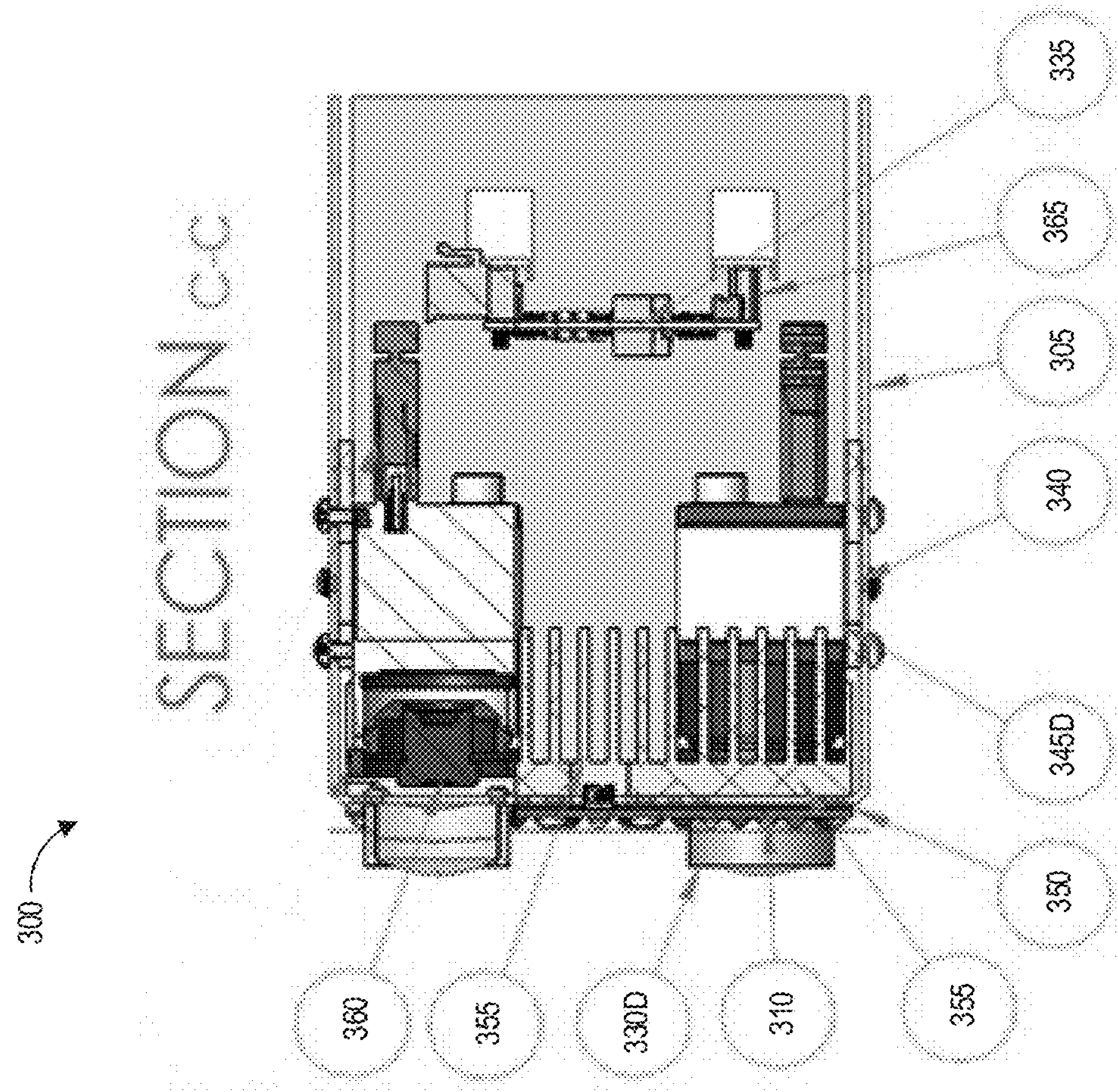
300
SECTION C-C
360
355
330D
310
355
350
345D
340
305
365
335

FIG. 4C

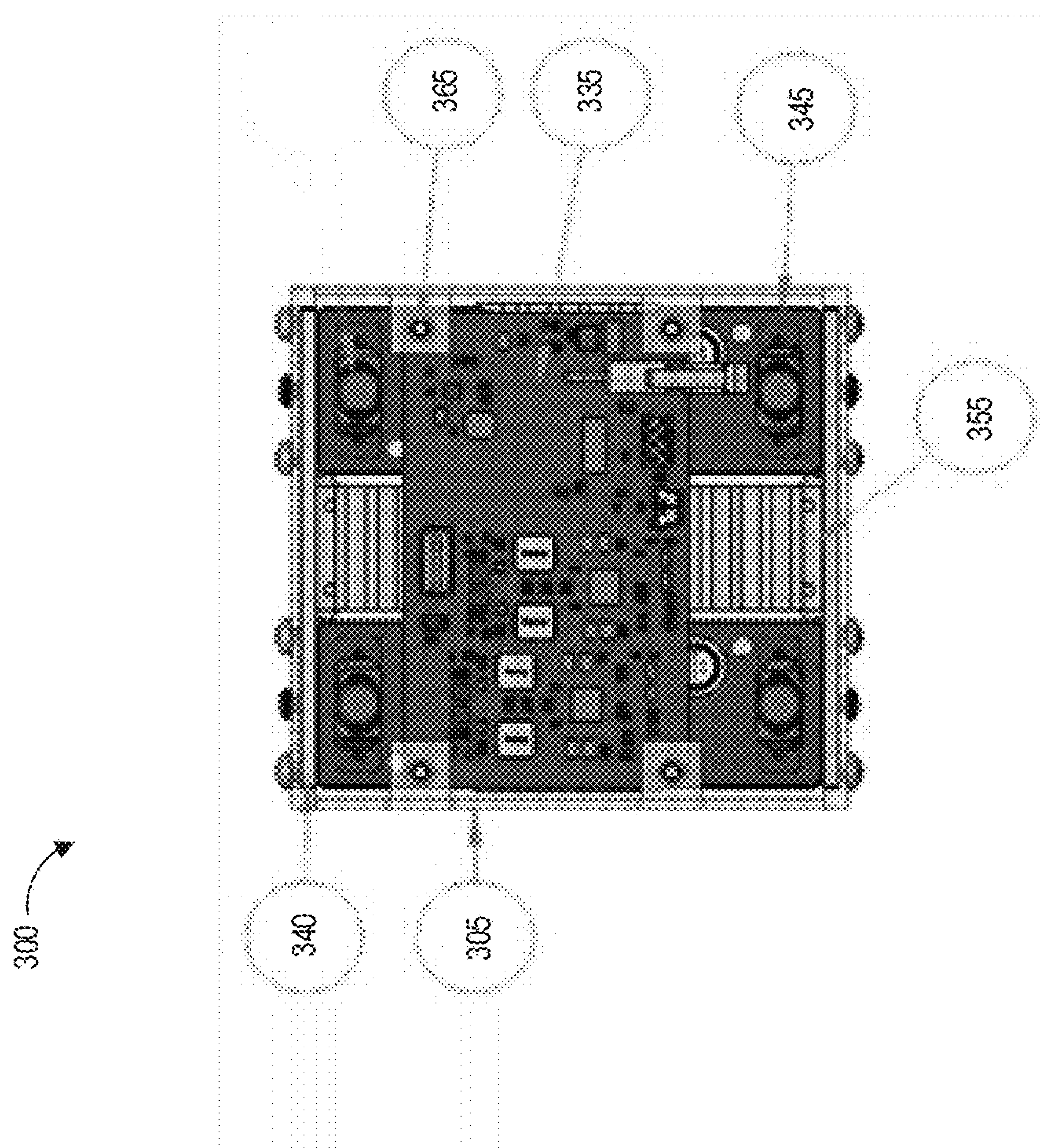

FIG. 4D

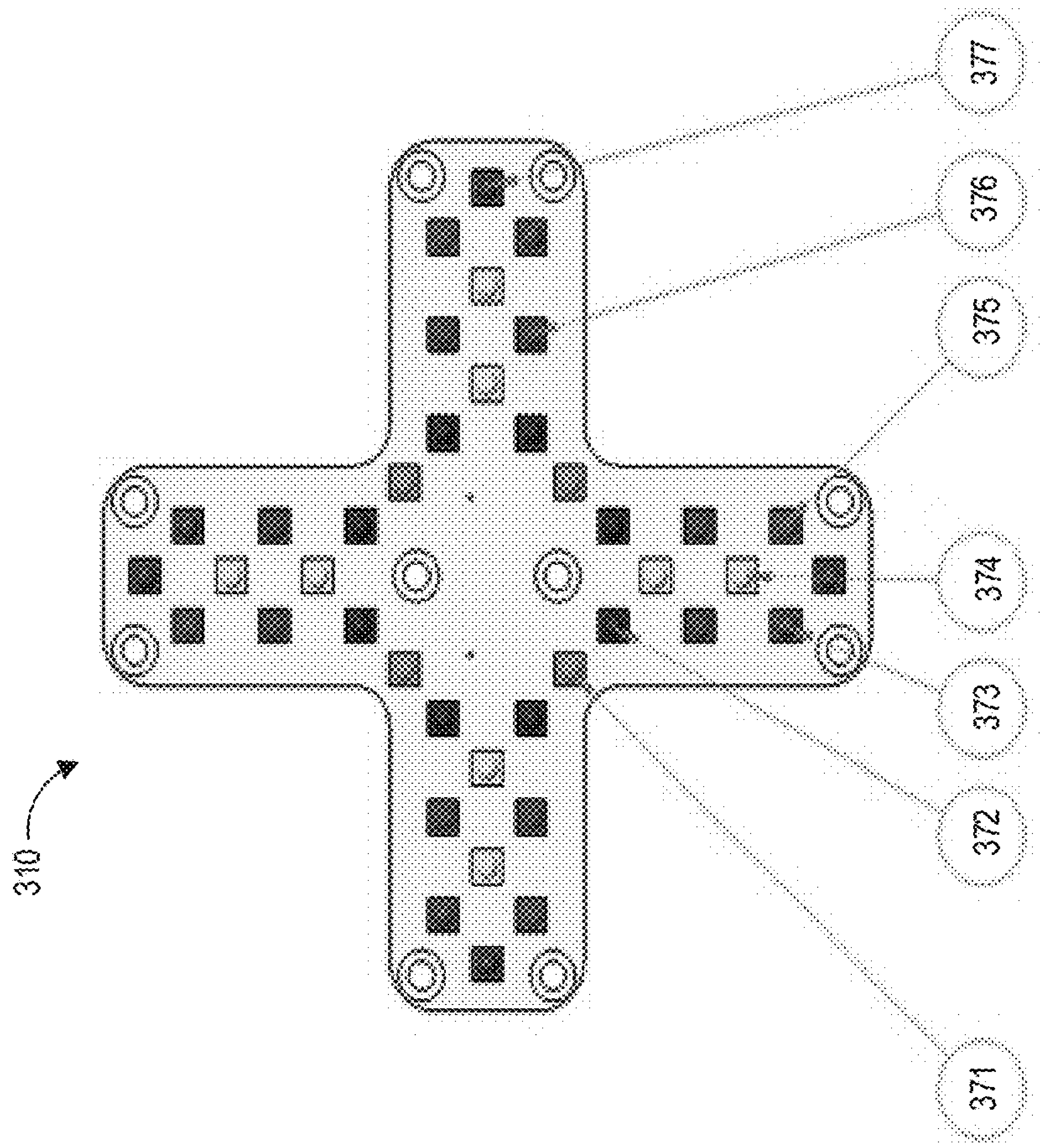

FIG. 4E

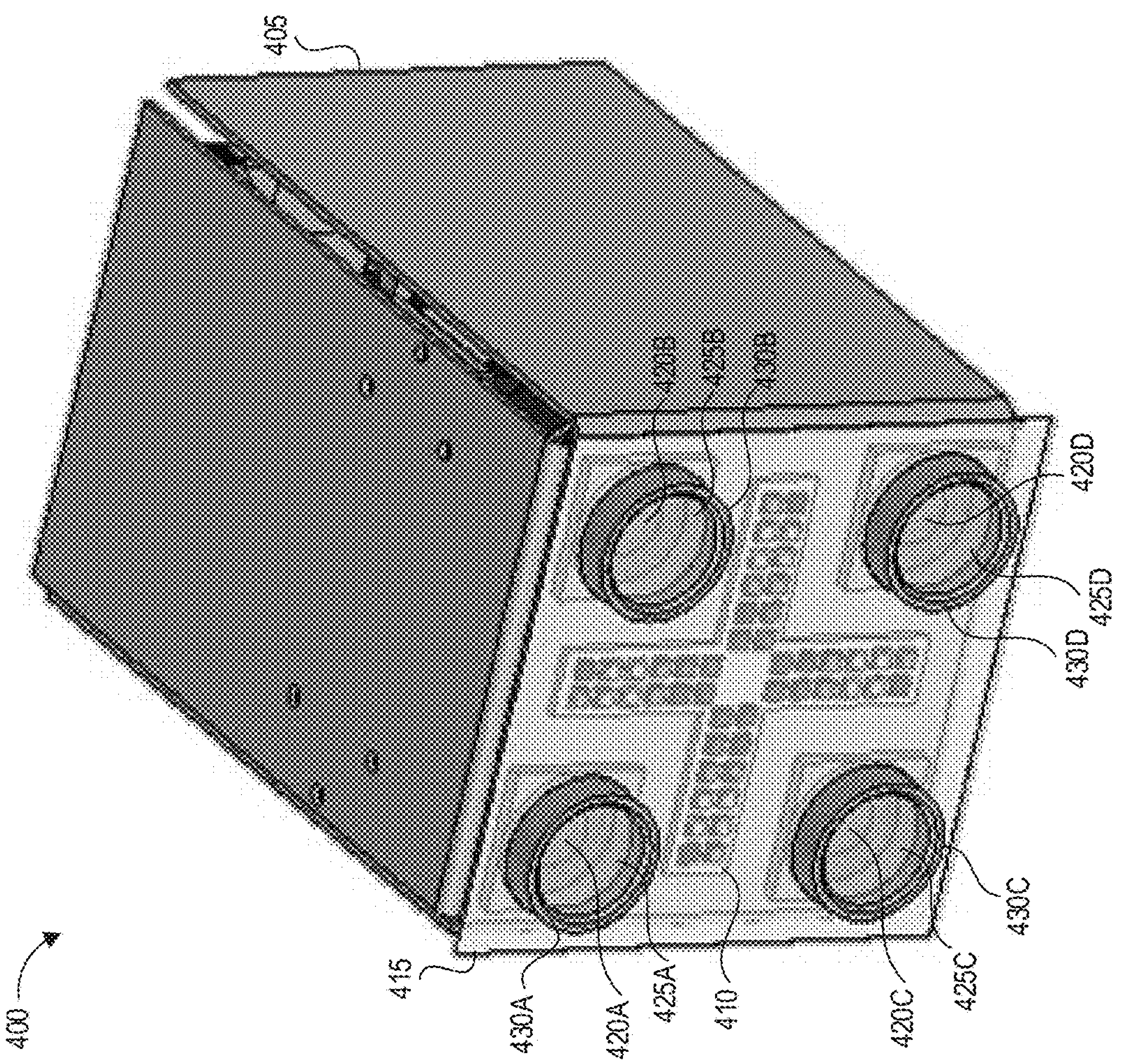
400
405
410
415
420A
420B
420C
420D
425A
425B
425C
425D
430A
430B
430C
430D

FIG. 5

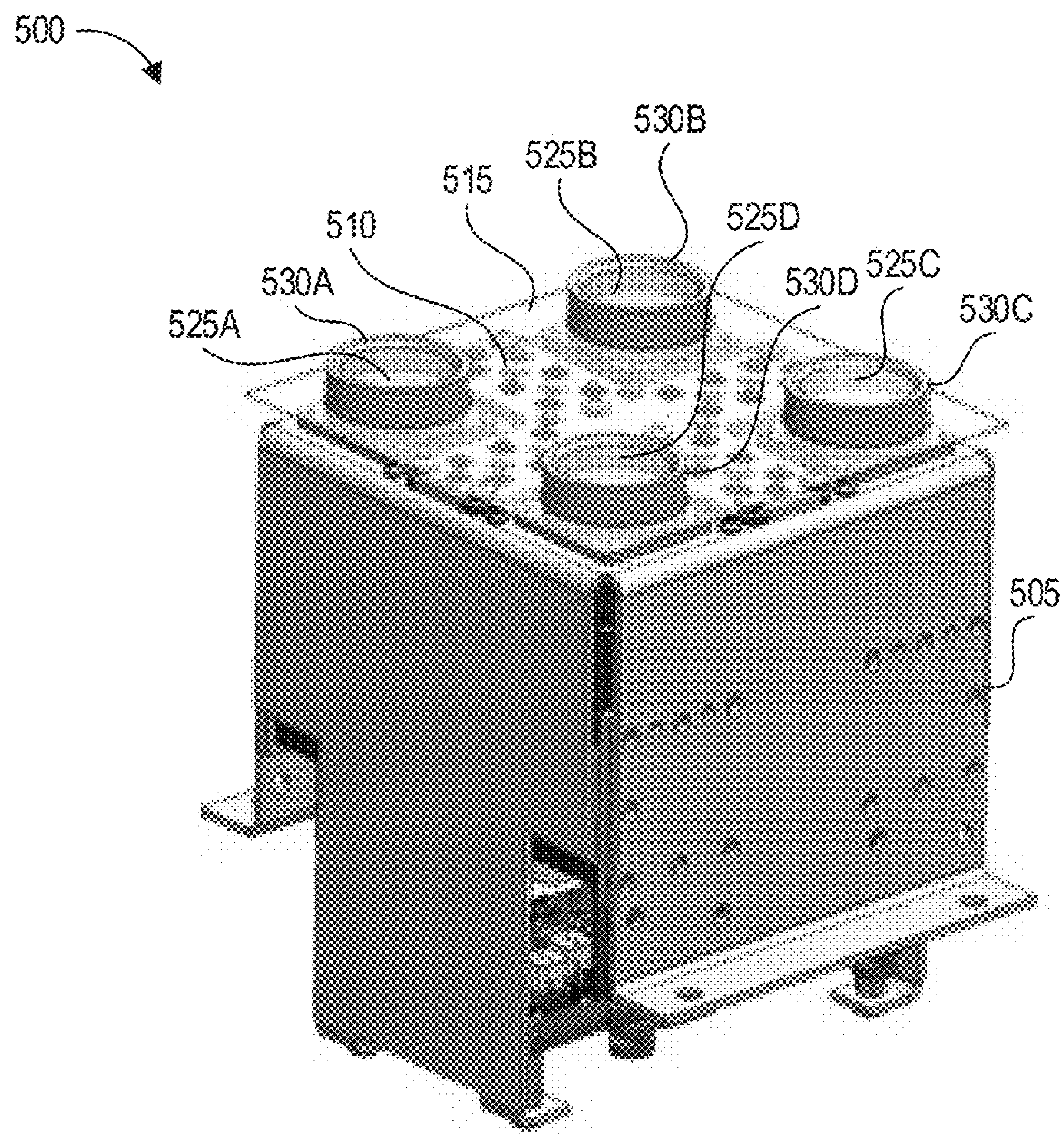

FIG. 6A

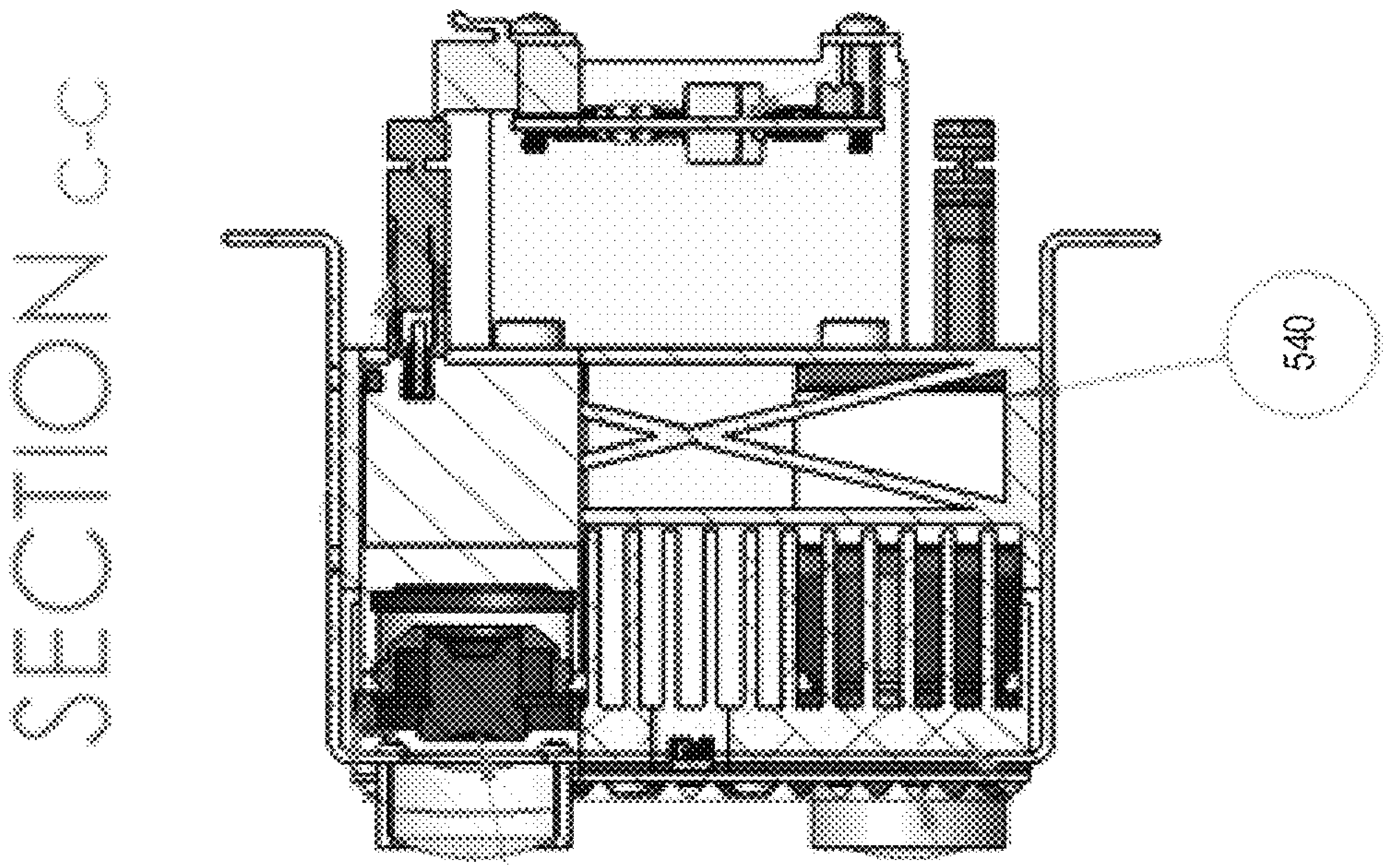

FIG. 6C

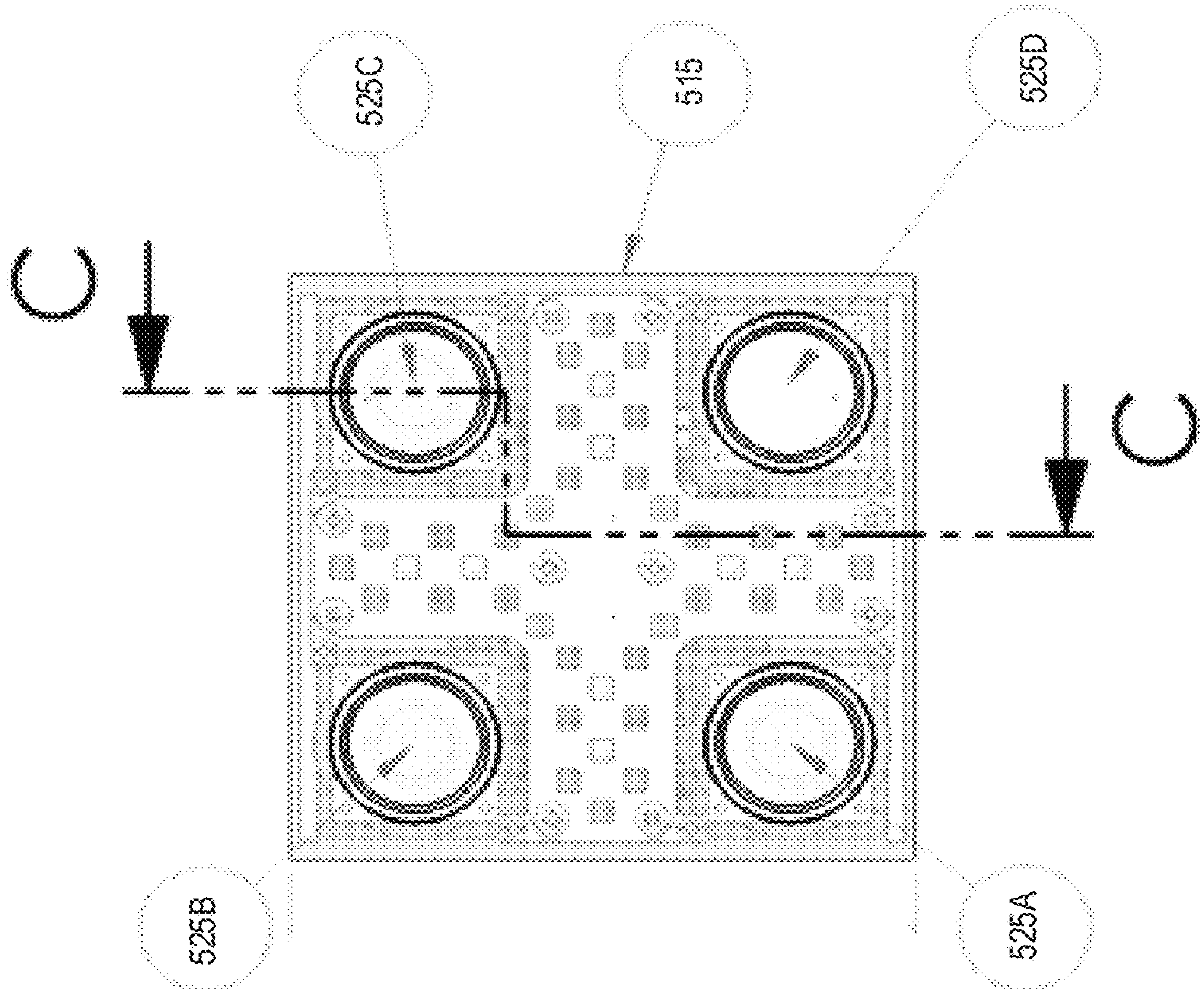

FIG. 6B

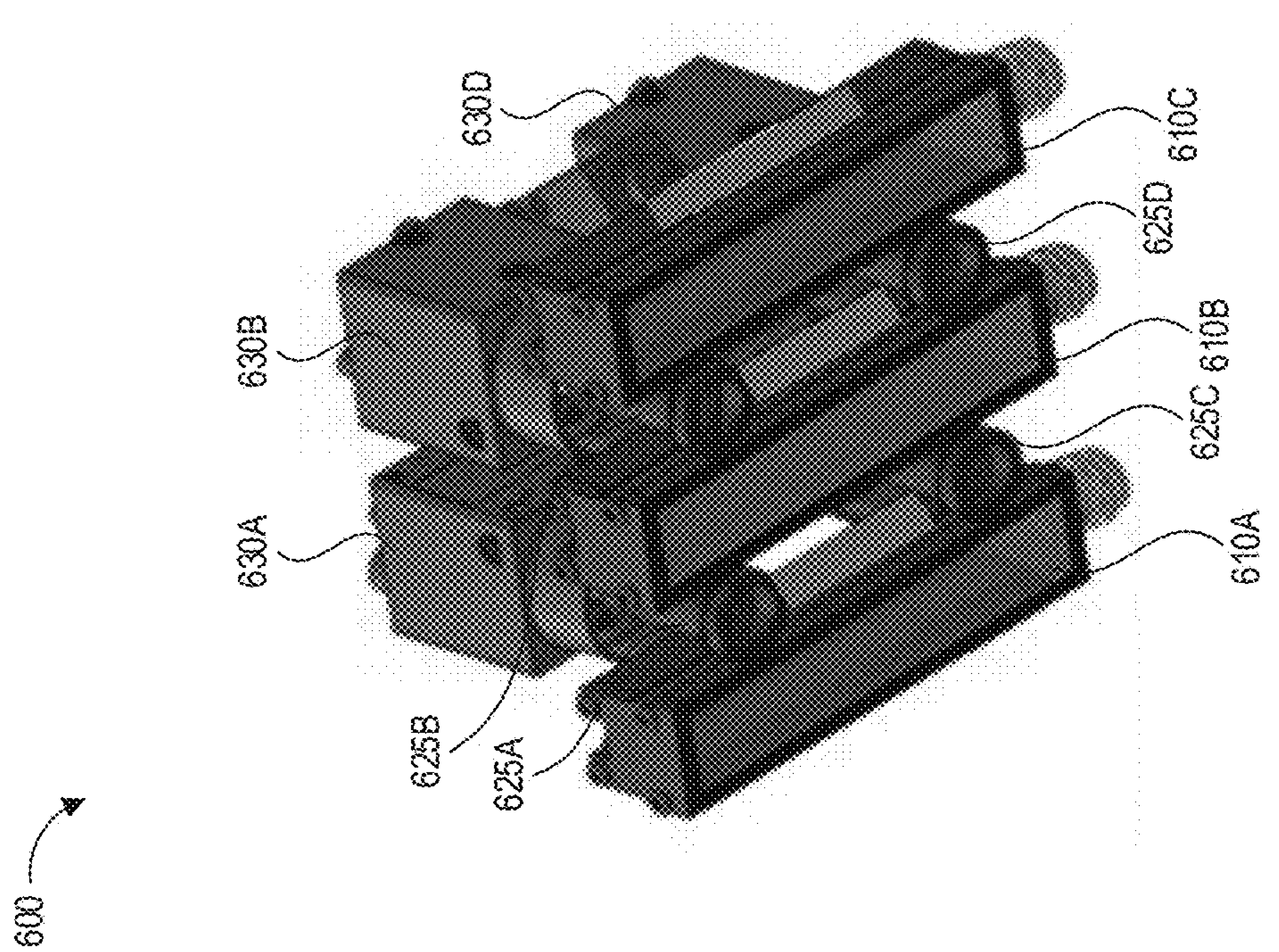
600
625B
625A
630A
630B
630D
610A
625C
610B
625D
610C

FIG. 7A

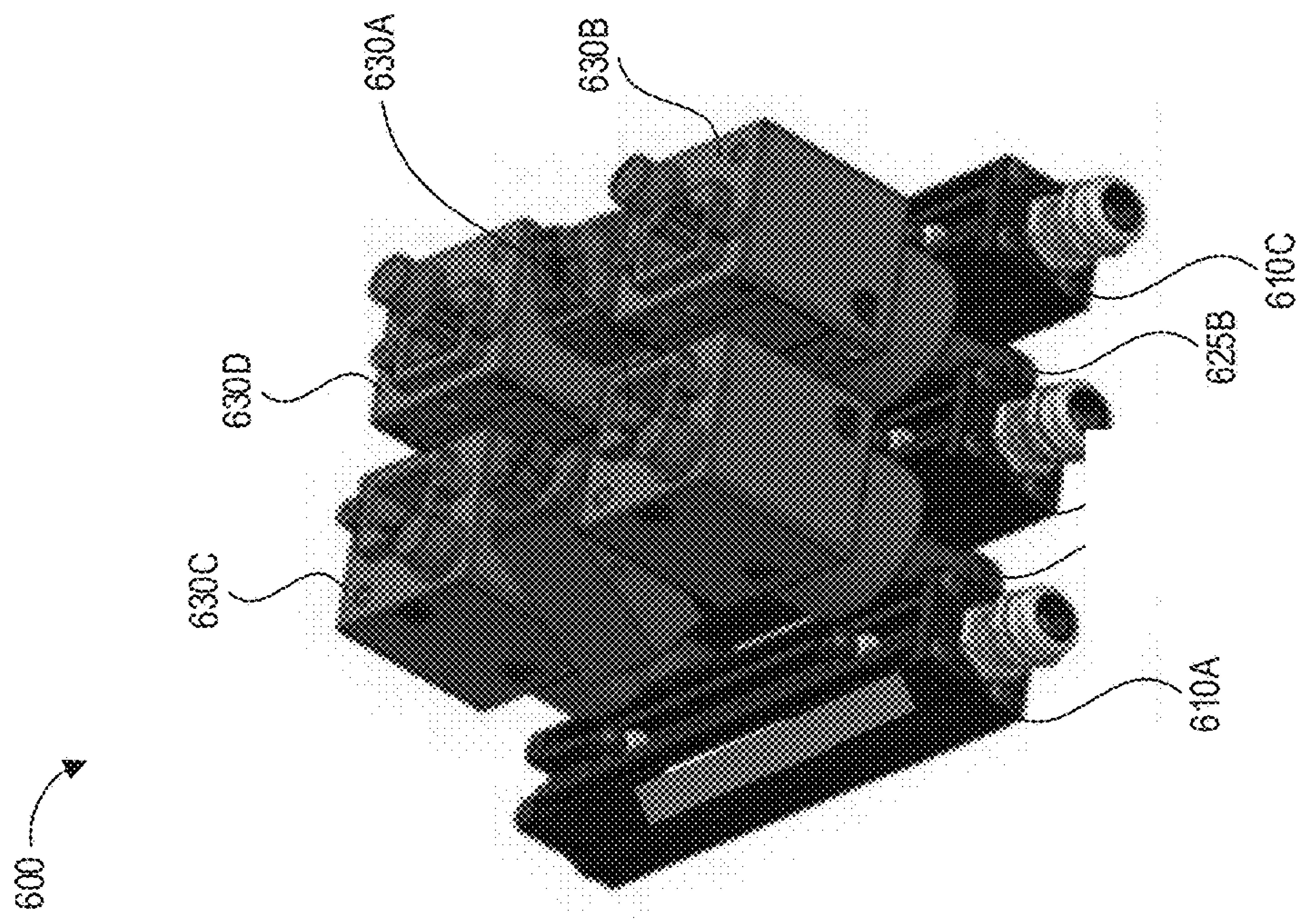
600
630C
630D
630A
630B
610A
625B
610C

FIG. 7B

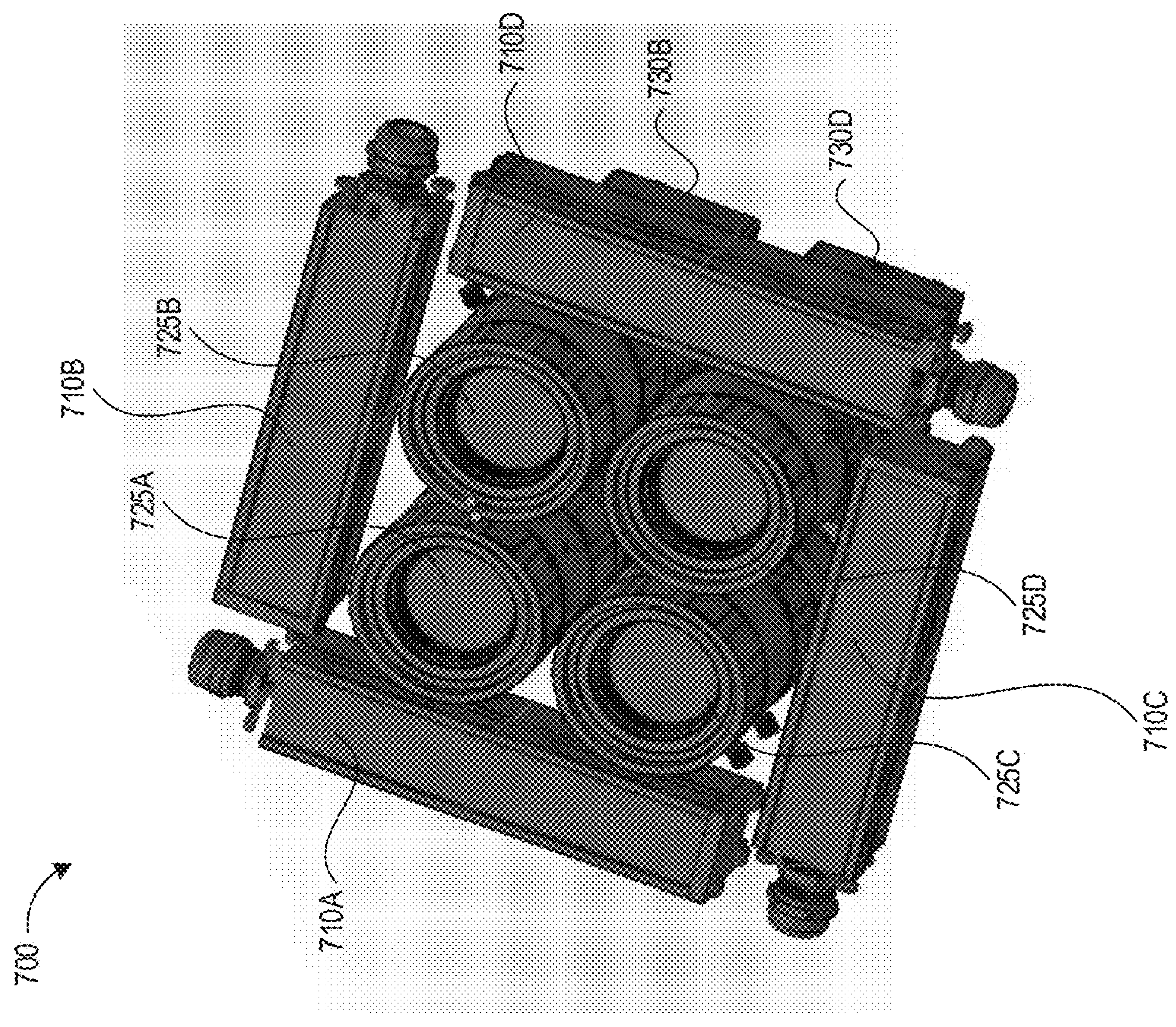
700
710A
710B
710C
710D
725A
725B
725C
725D
730B
730D

FIG. 8A

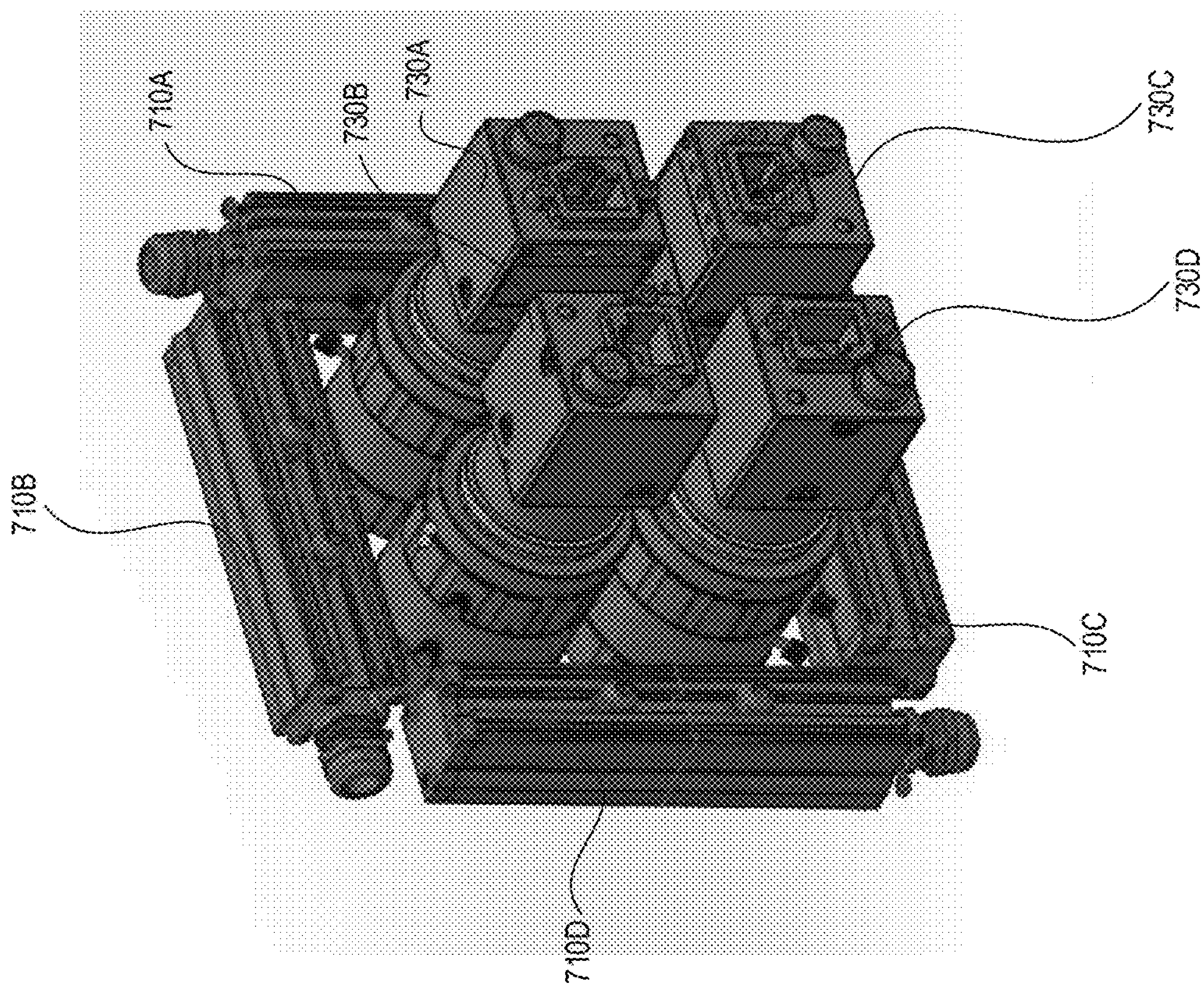
710A
710B
710C
710D
730A
730B
730C
730D

FIG. 8B

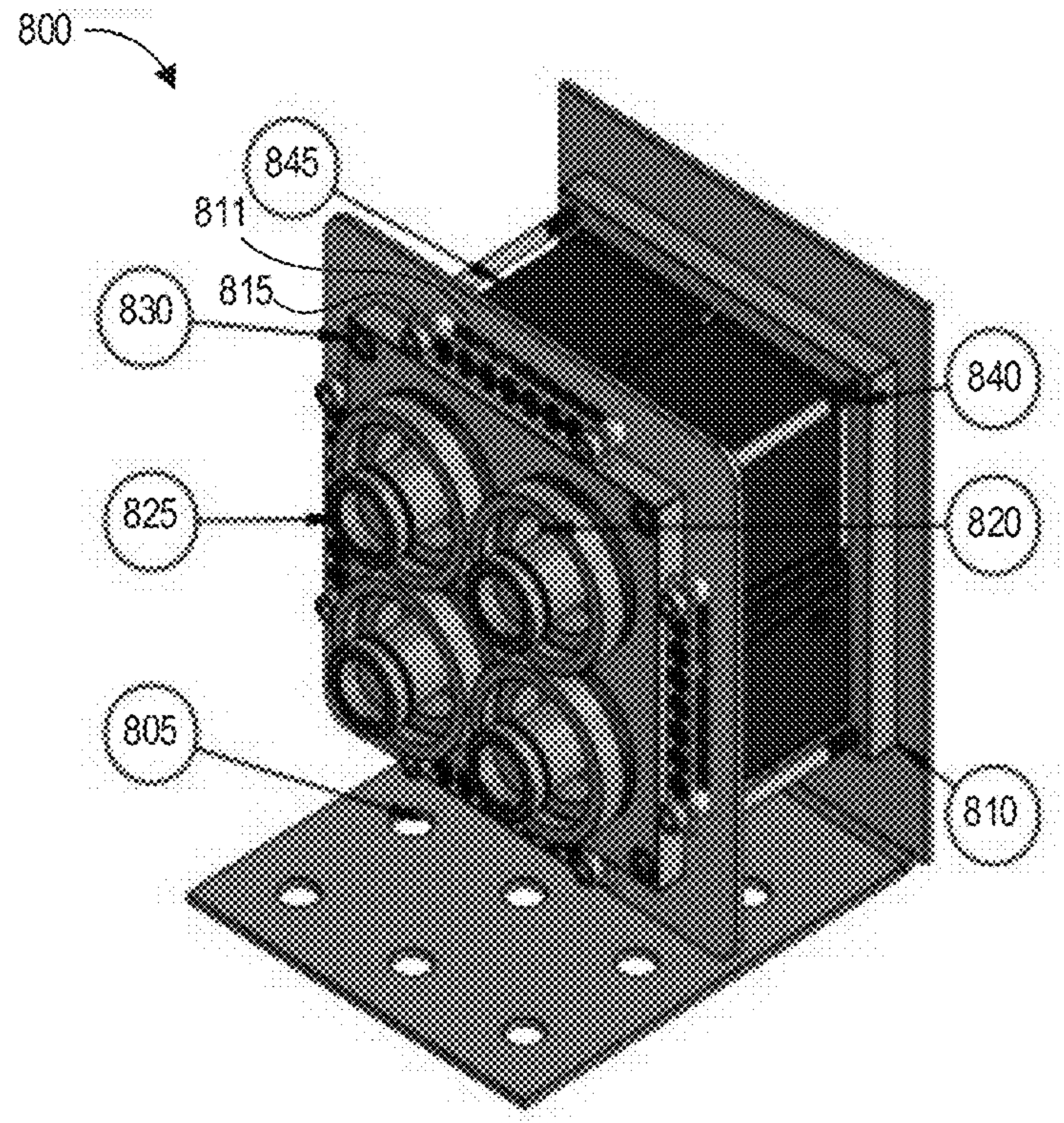

FIG. 9A

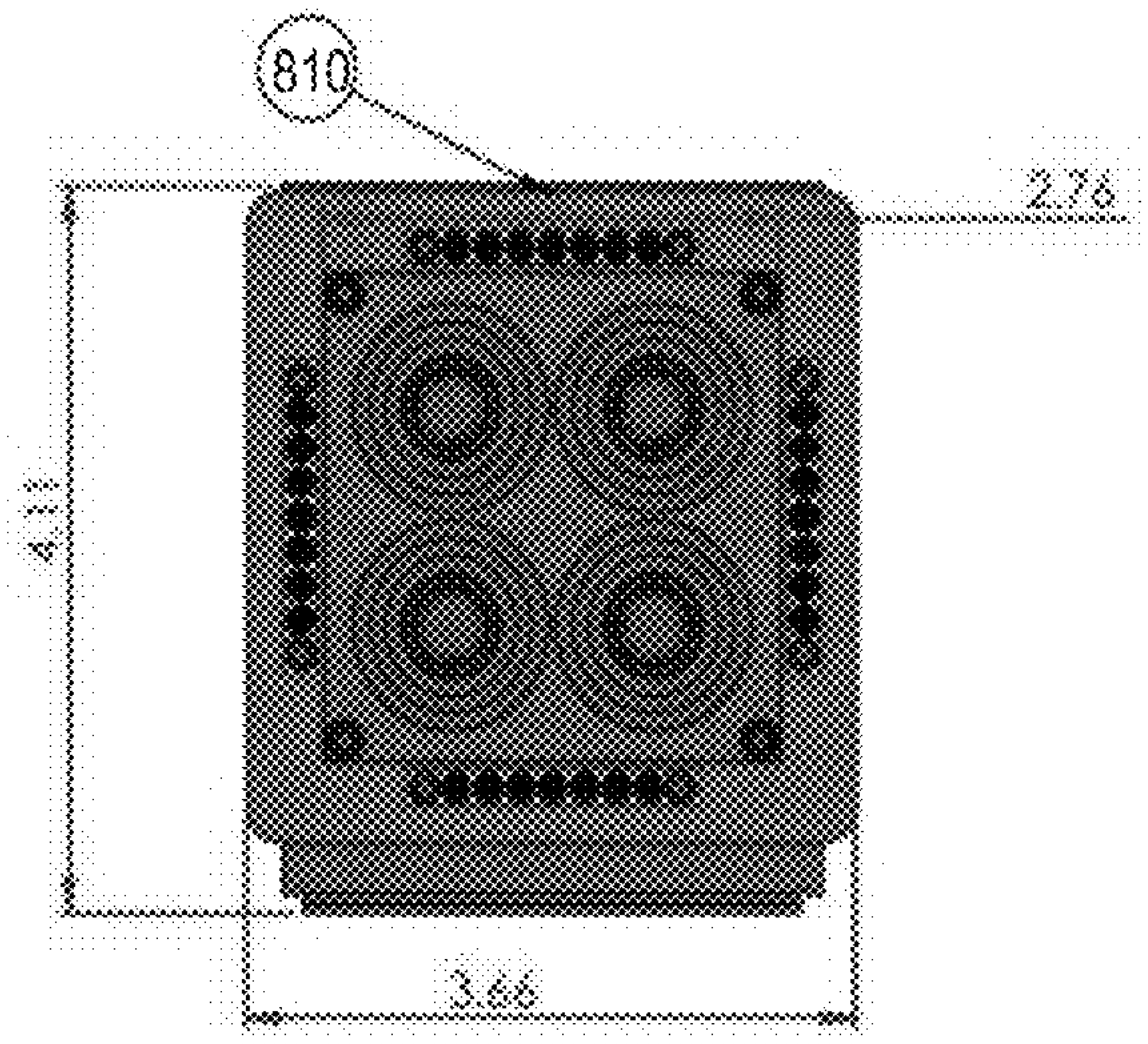

FIG. 9B

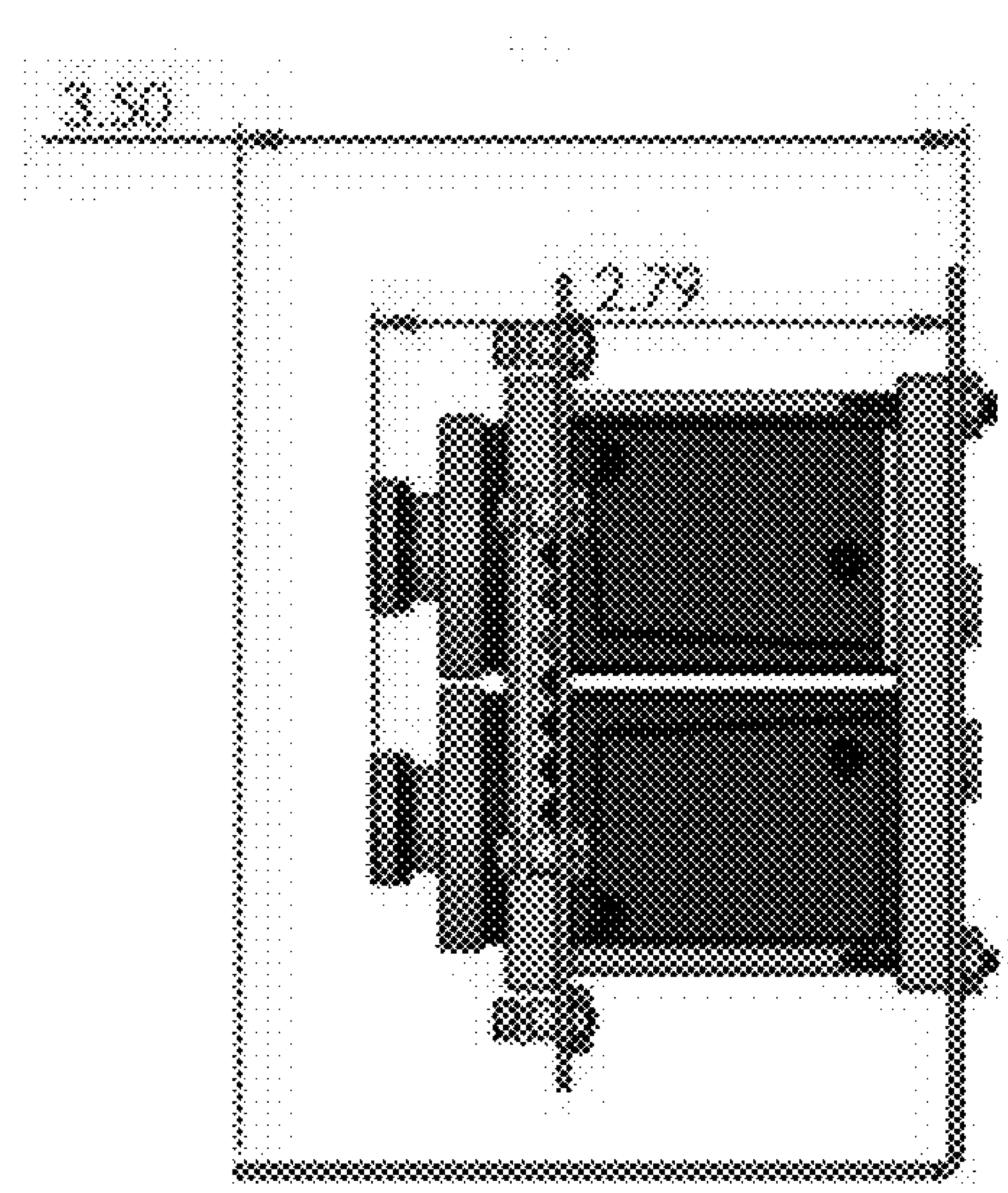

FIG. 9C

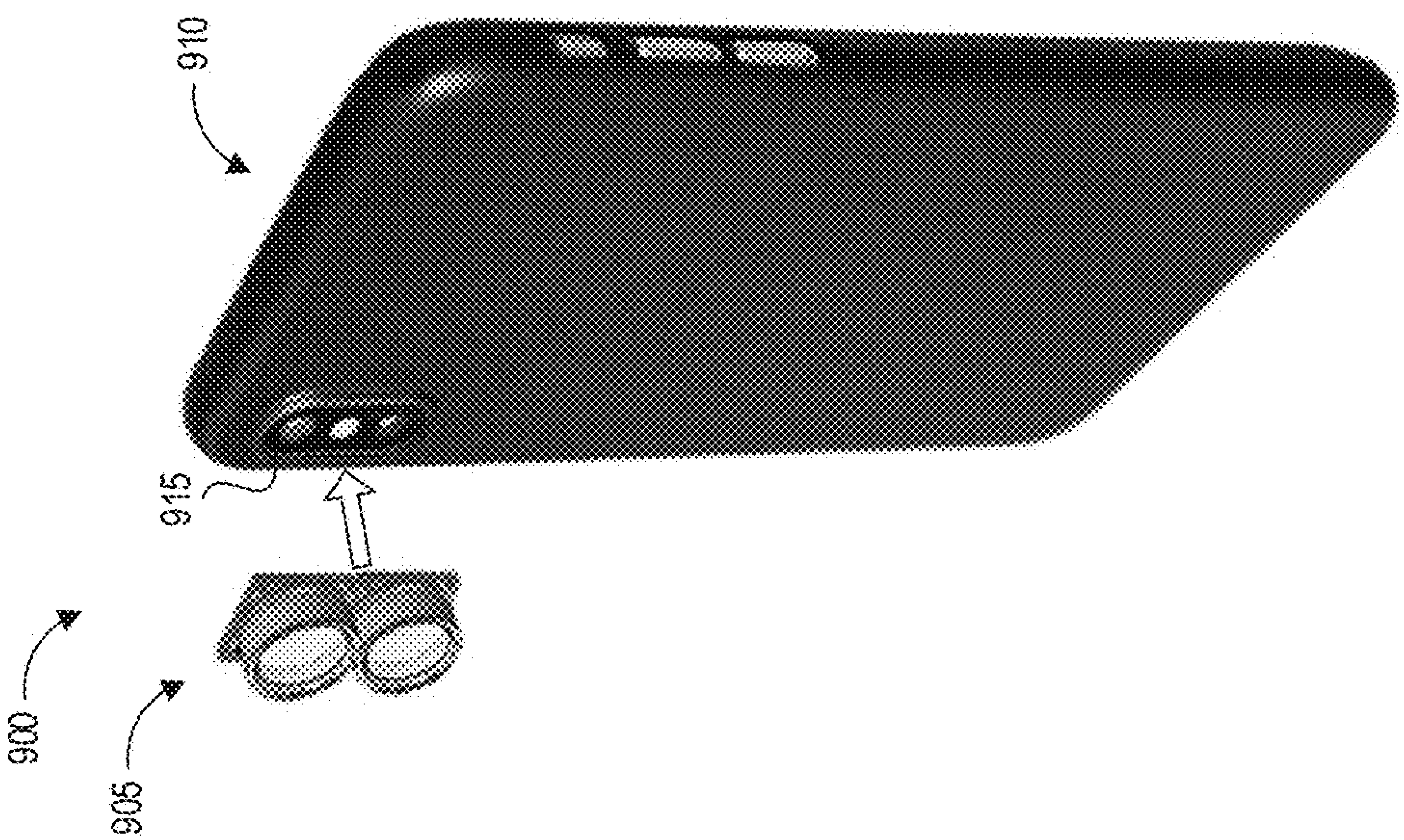

FIG. 10A

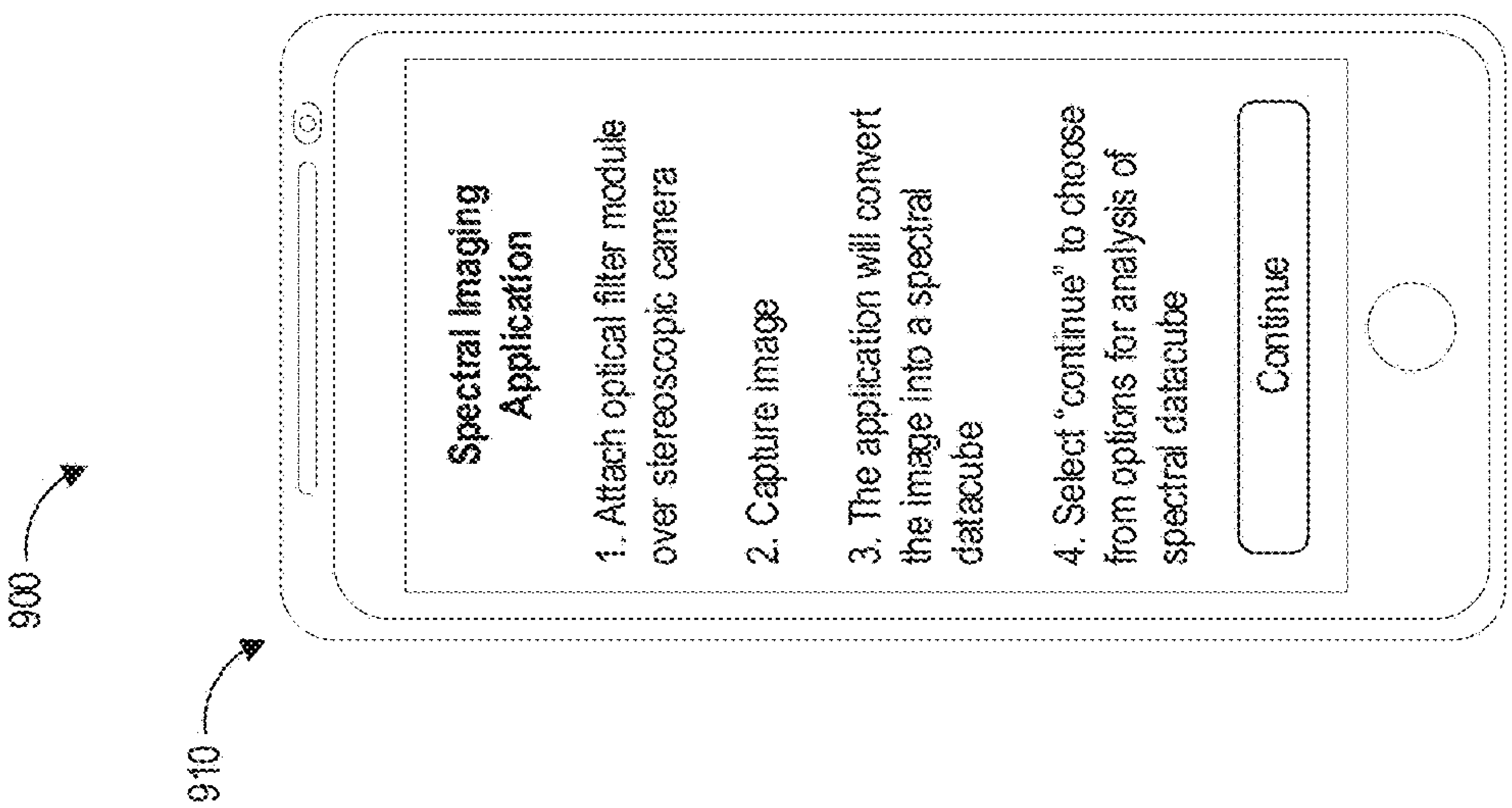

FIG. 10B

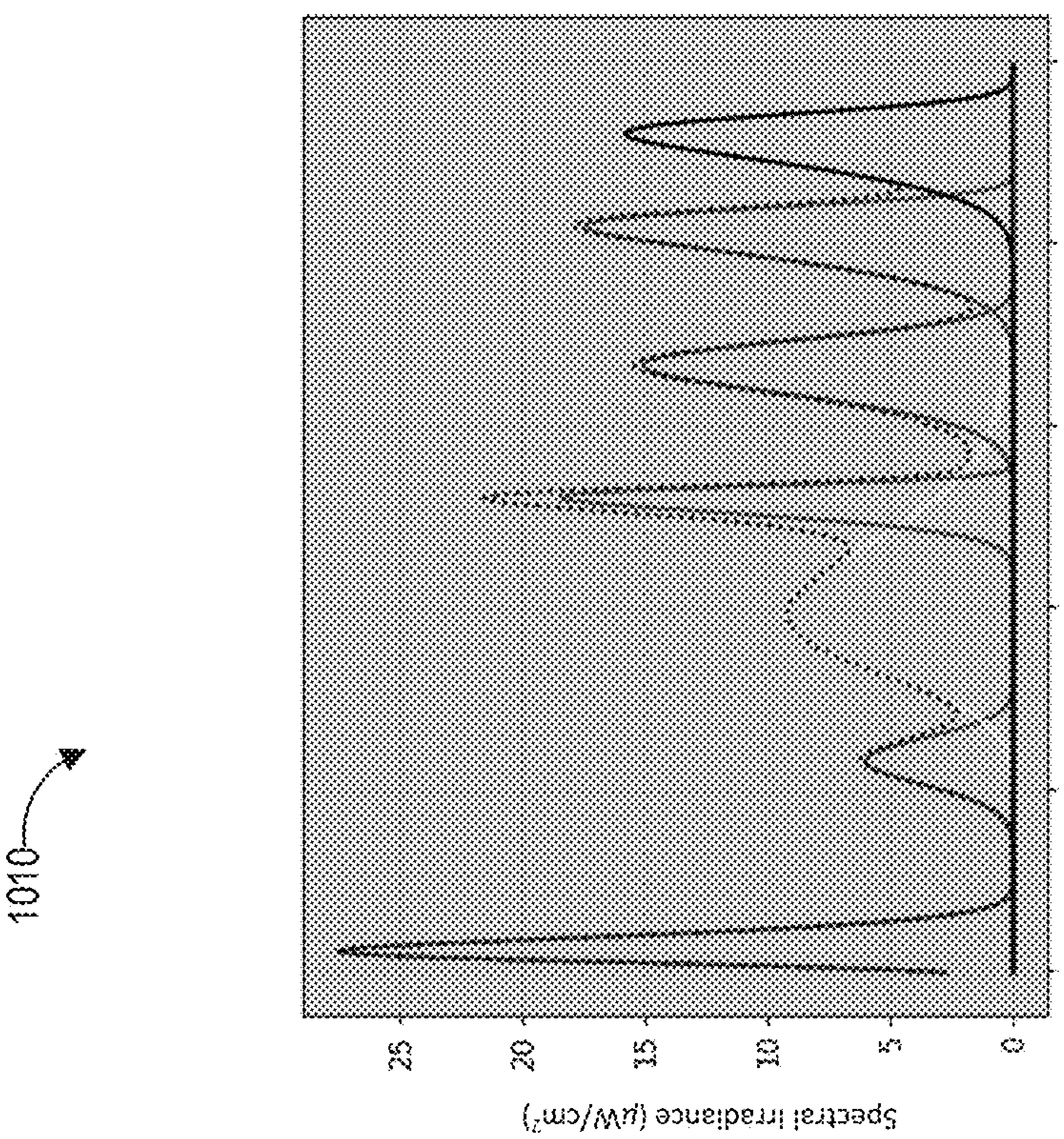

FIG. 11B

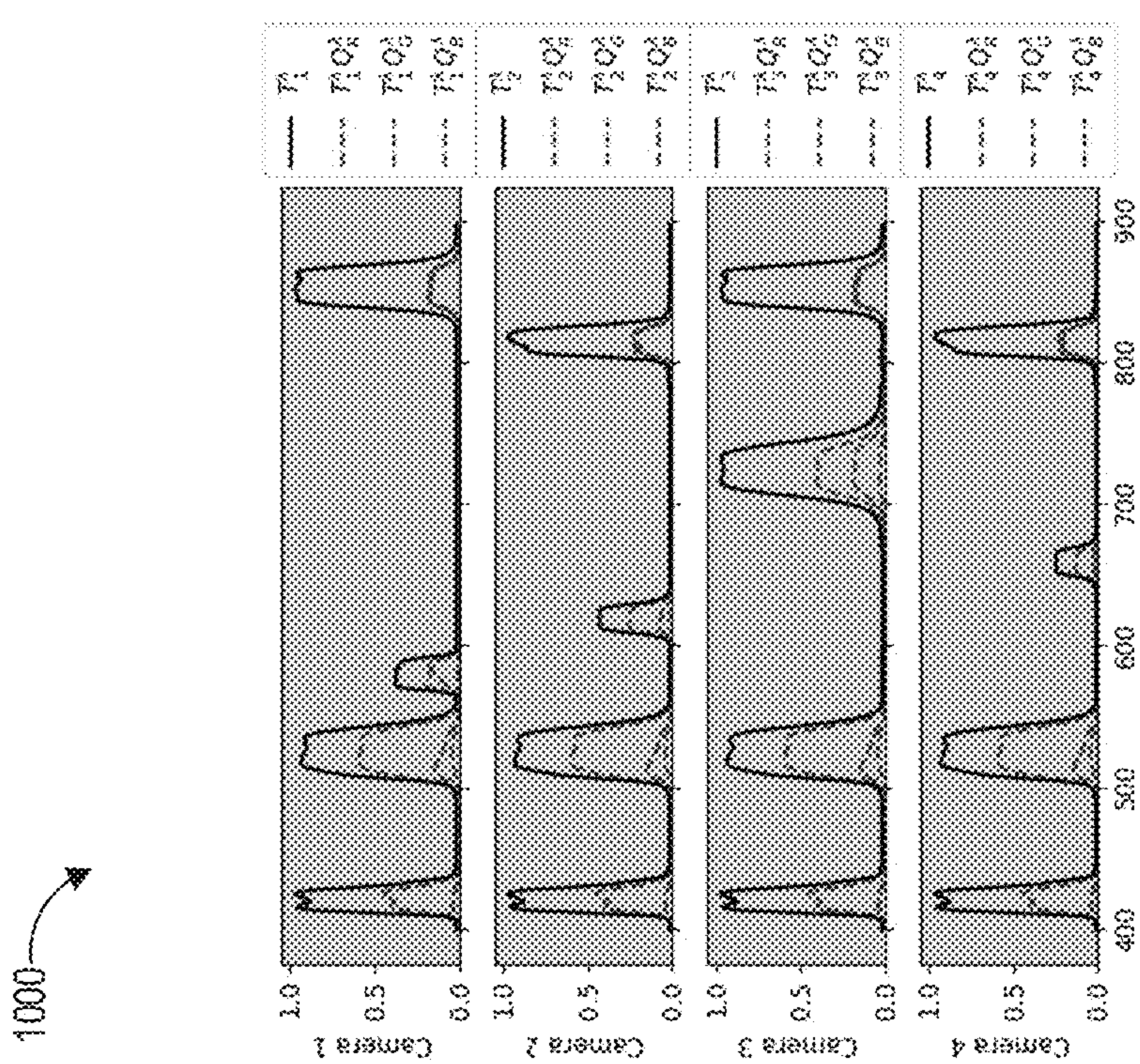

FIG. 11A

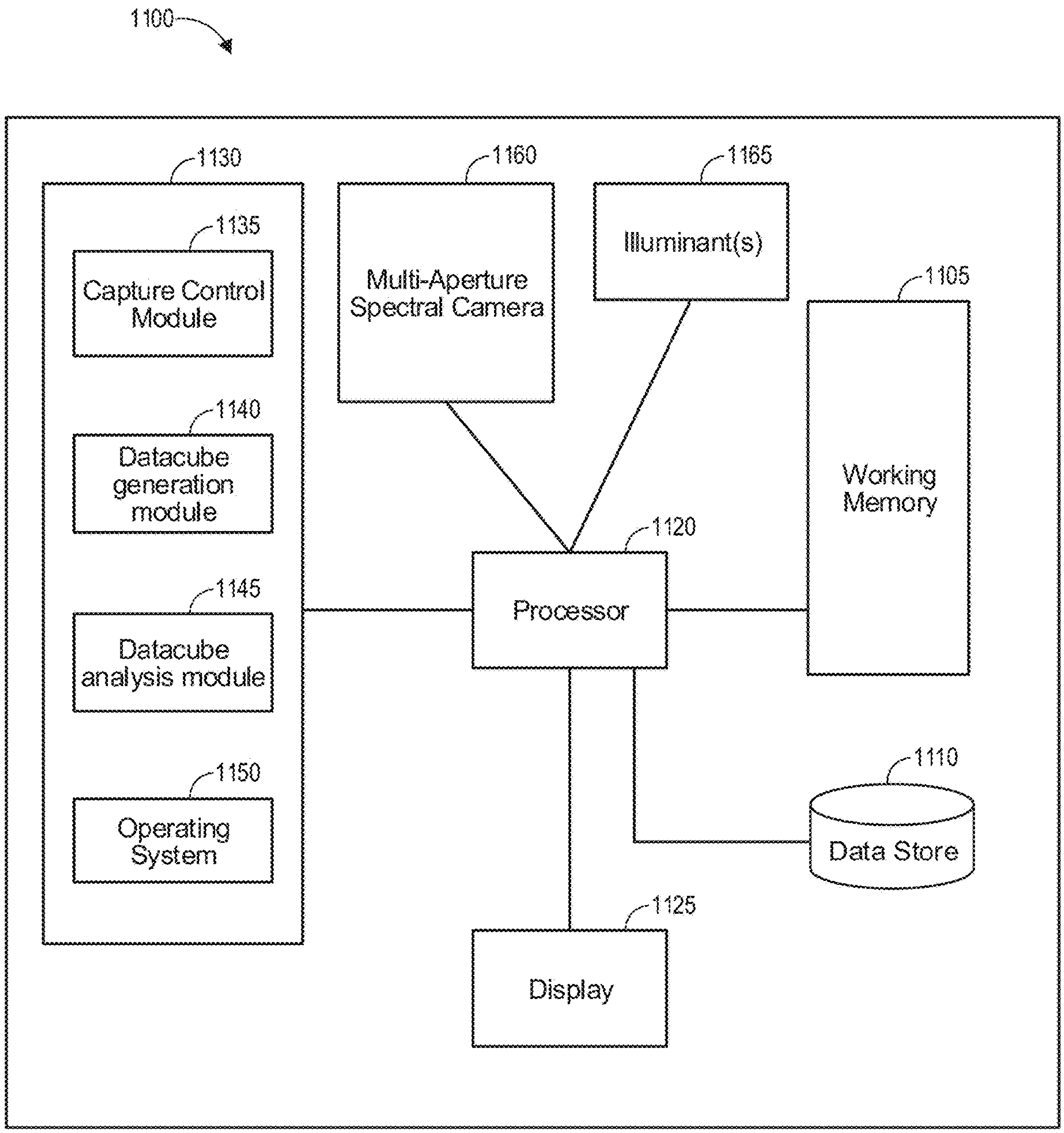
1100
1130
1135
Capture Control Module
1140
Datacube generation module
1145
Datacube analysis module
1150
Operating System
1160
Multi-Aperture Spectral Camera
1165
Illuminant(s)
1105
Working Memory
1120
Processor
1110
Data Store
1125
Display

FIG. 12

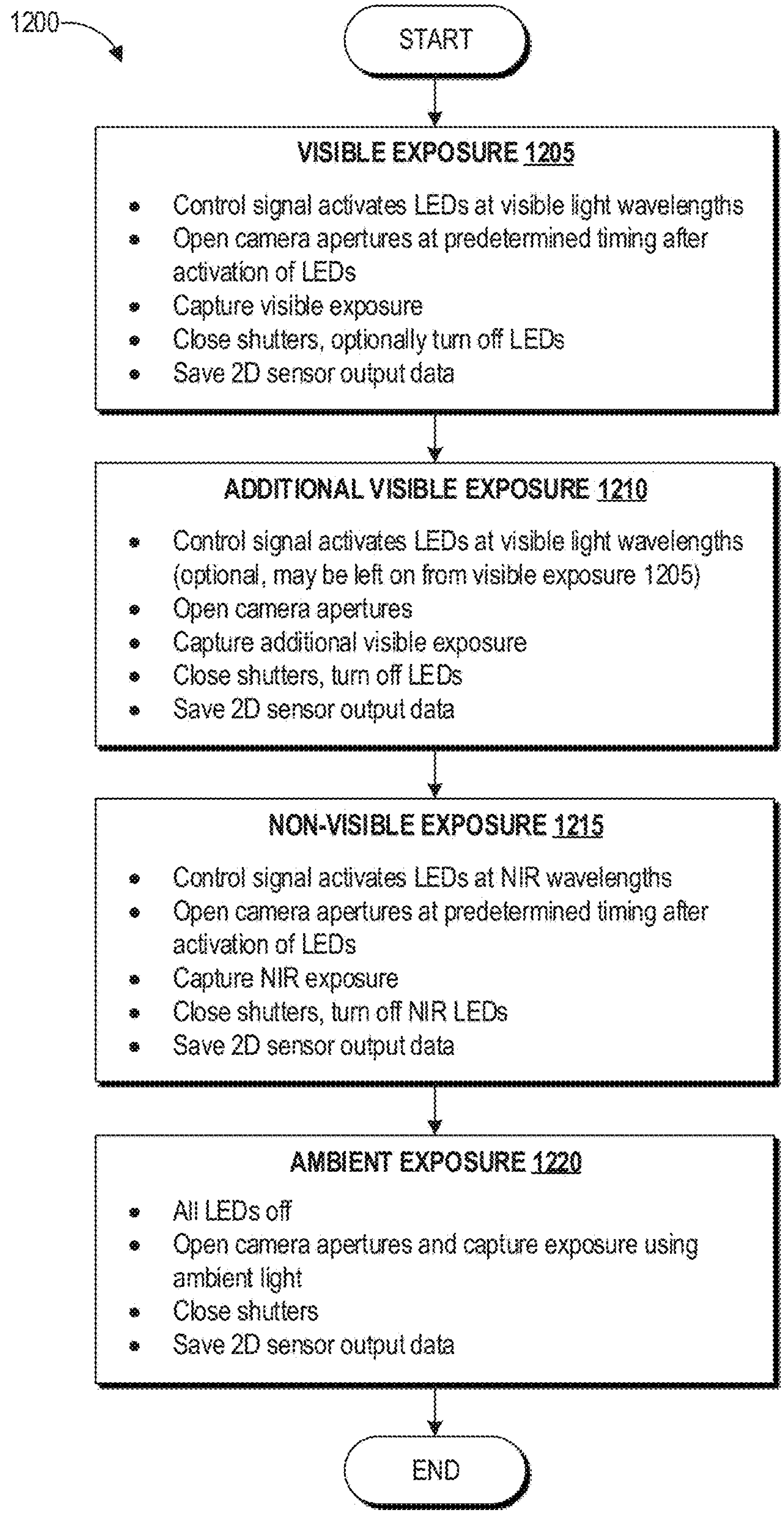
1200
START
VISIBLE EXPOSURE 1205
Control signal activates LEDs at visible light wavelengths
Open camera apertures at predetermined timing after activation of LEDs
Capture visible exposure
Close shutters, optionally turn off LEDs
Save 2D sensor output data
ADDITIONAL VISIBLE EXPOSURE 1210
Control signal activates LEDs at visible light wavelengths (optional, may be left on from visible exposure 1205)
Open camera apertures
Capture additional visible exposure
Close shutters, turn off LEDs
Save 2D sensor output data
NON-VISIBLE EXPOSURE 1215
Control signal activates LEDs at NIR wavelengths
Open camera apertures at predetermined timing after activation of LEDs
Capture NIR exposure
Close shutters, turn off NIR LEDs
Save 2D sensor output data
AMBIENT EXPOSURE 1220
All LEDs off
Open camera apertures and capture exposure using ambient light
Close shutters
Save 2D sensor output data
END

FIG. 13

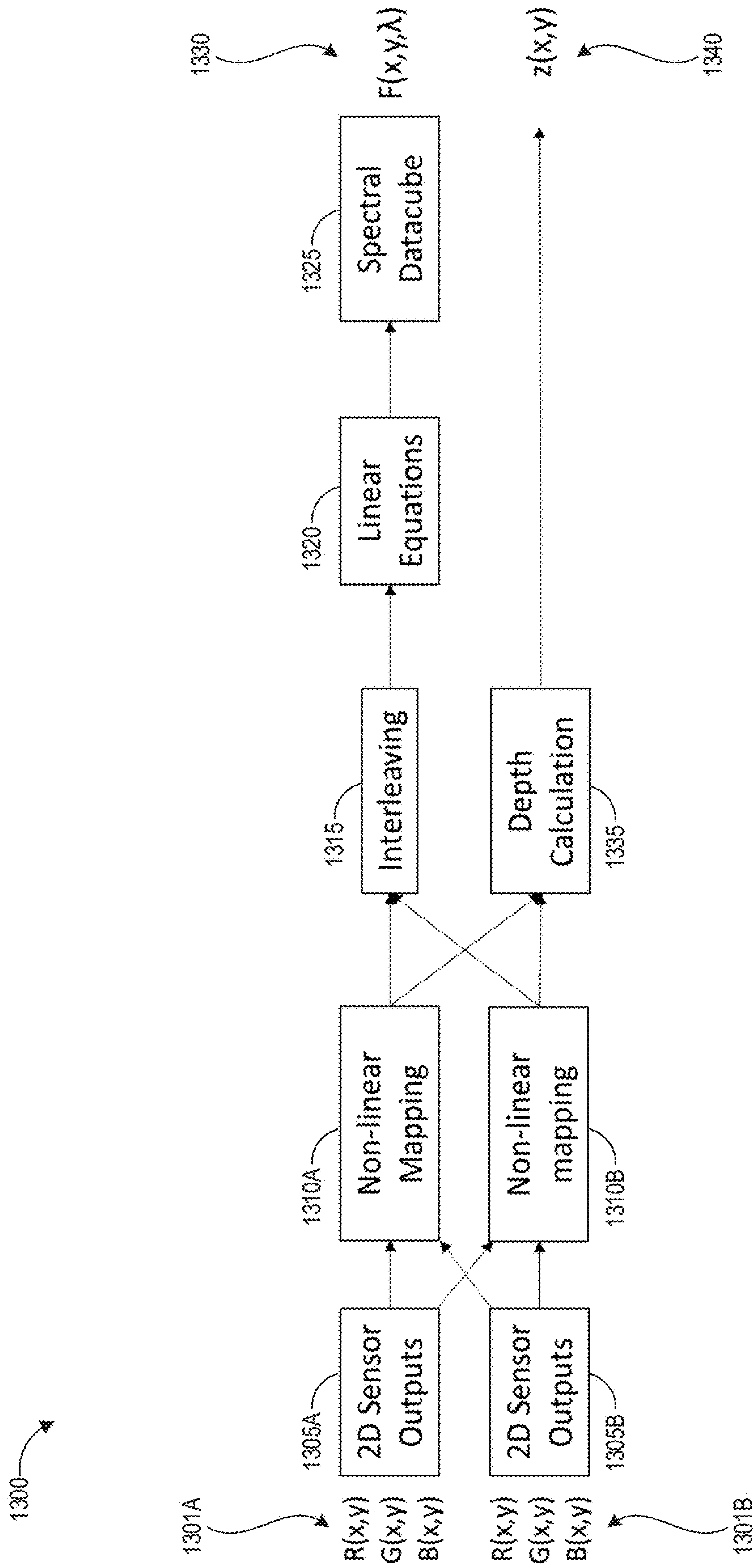
1300
1301A
R(x,y)
G(x,y)
B(x,y)
R(x,y)
G(x,y)
B(x,y)
1301B
1305A
2D Sensor Outputs
2D Sensor Outputs
1305B
1310A
Non-linear Mapping
Non-linear mapping
1310B
1315
Interleaving
Depth Calculation
1335
1320
Linear Equations
1325
Spectral Datacube
1330
F(x,y,λ)
z(x,y)
1340

FIG. 14

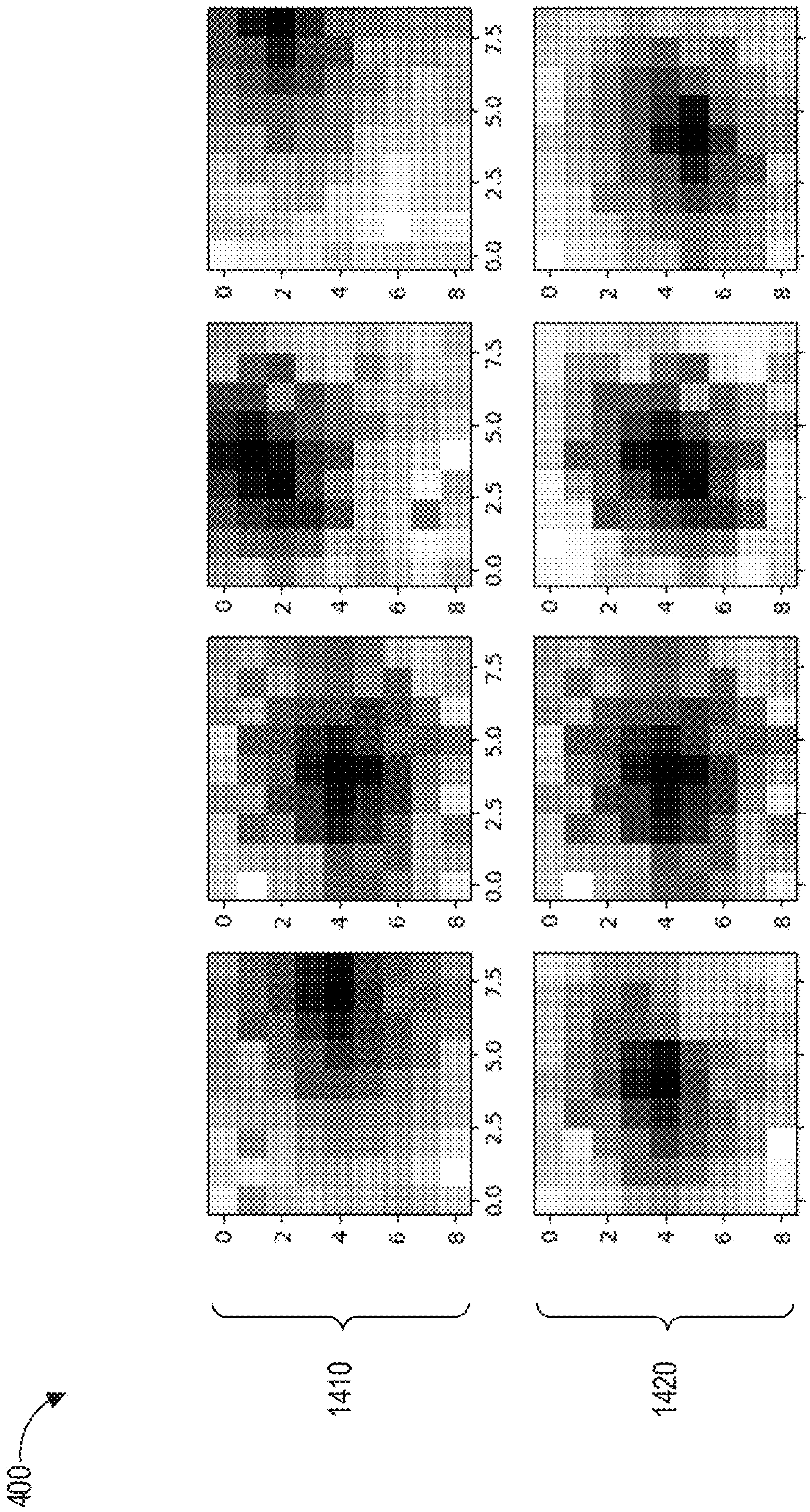

FIG. 15

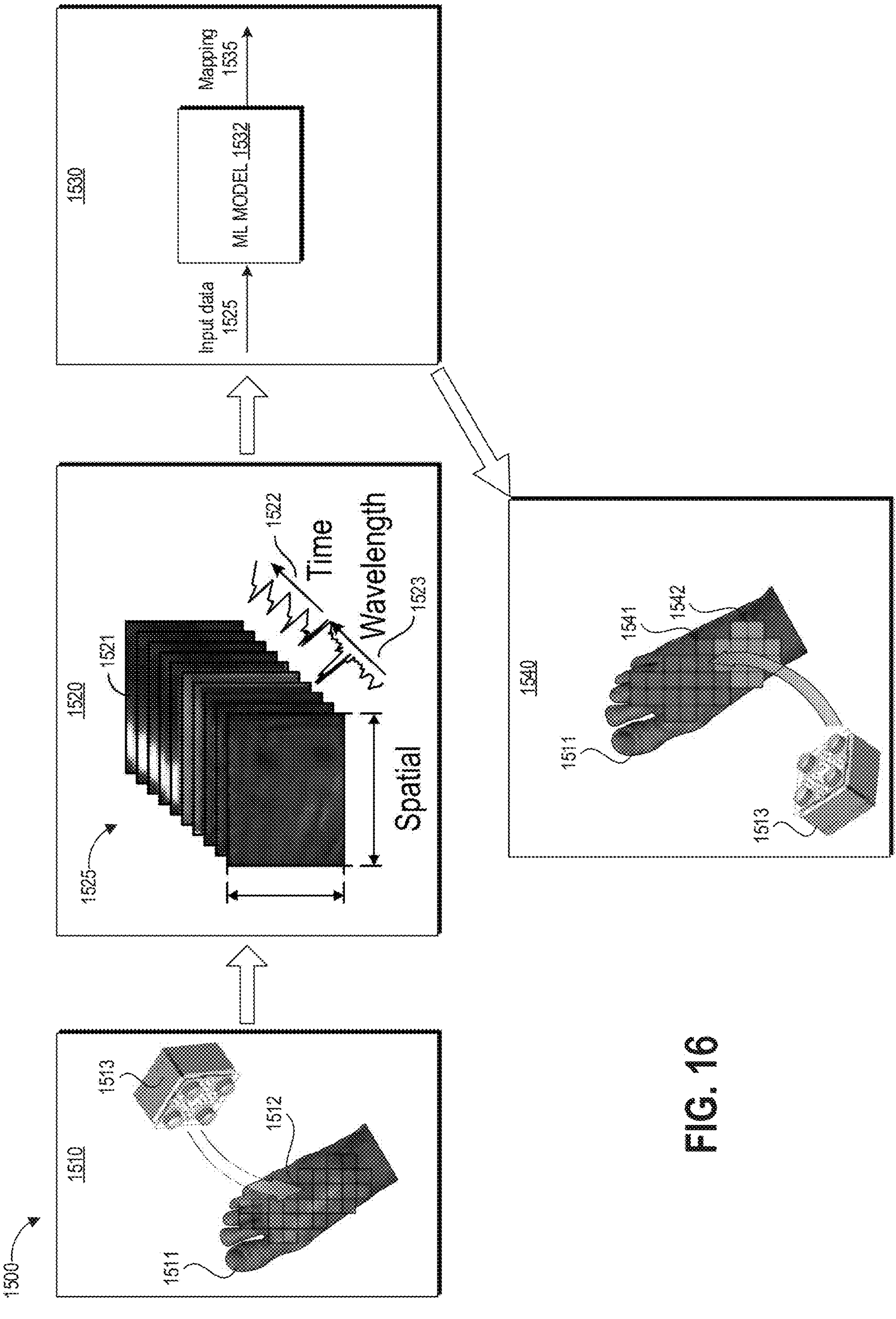
1500
1510
1513
1512
1511
1520
1525
1521
1522
Time
Wavelength
1523
Spatial
1530
Input data
1525
ML MODEL 1532
Mapping
1535
1540
1541
1542
1511
1513

FIG. 16

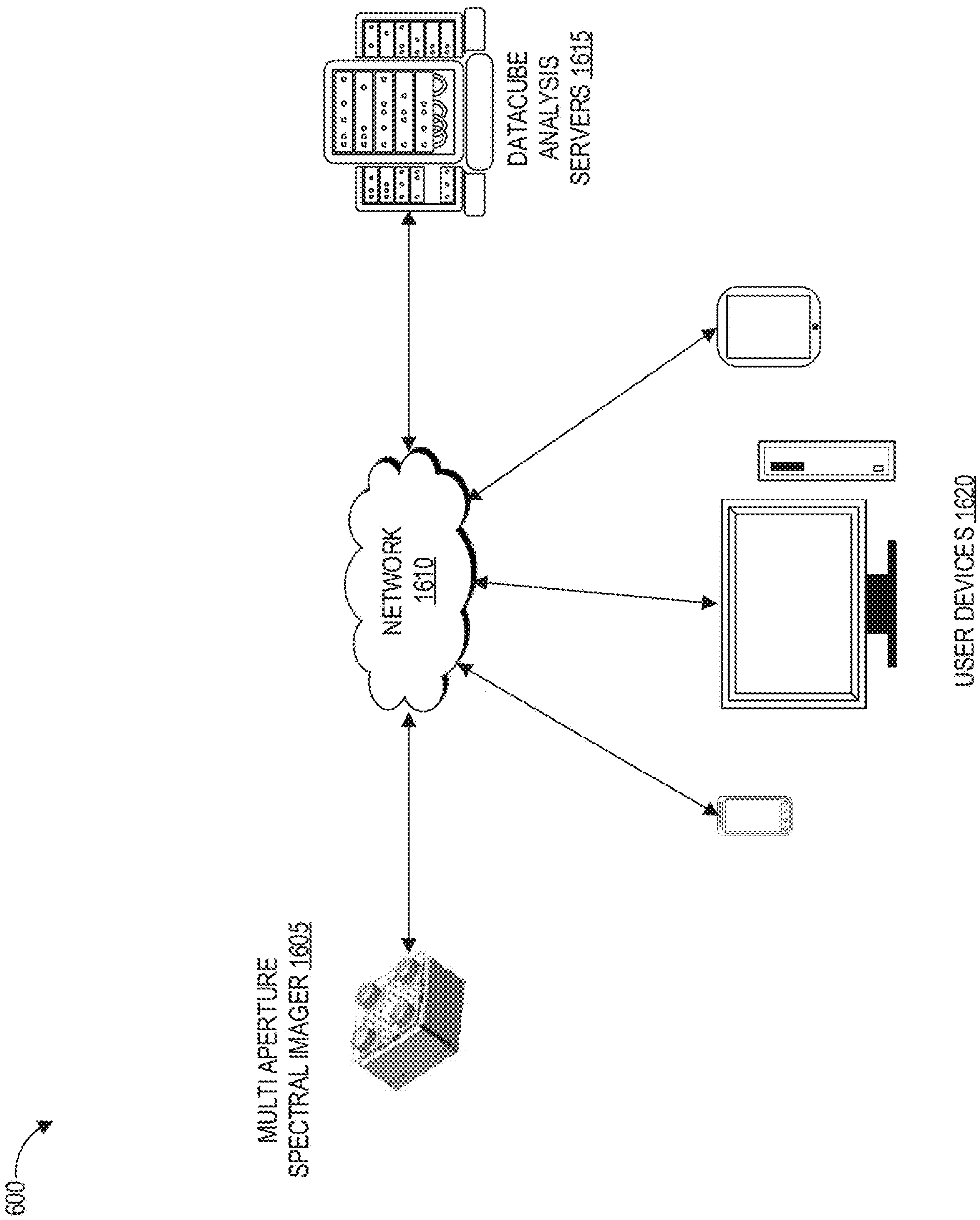
1600
MULTI APERTURE SPECTRAL IMAGER 1605
NETWORK 1610
DATACUBE ANALYSIS SERVERS 1615
USER DEVICES 1620

FIG. 17

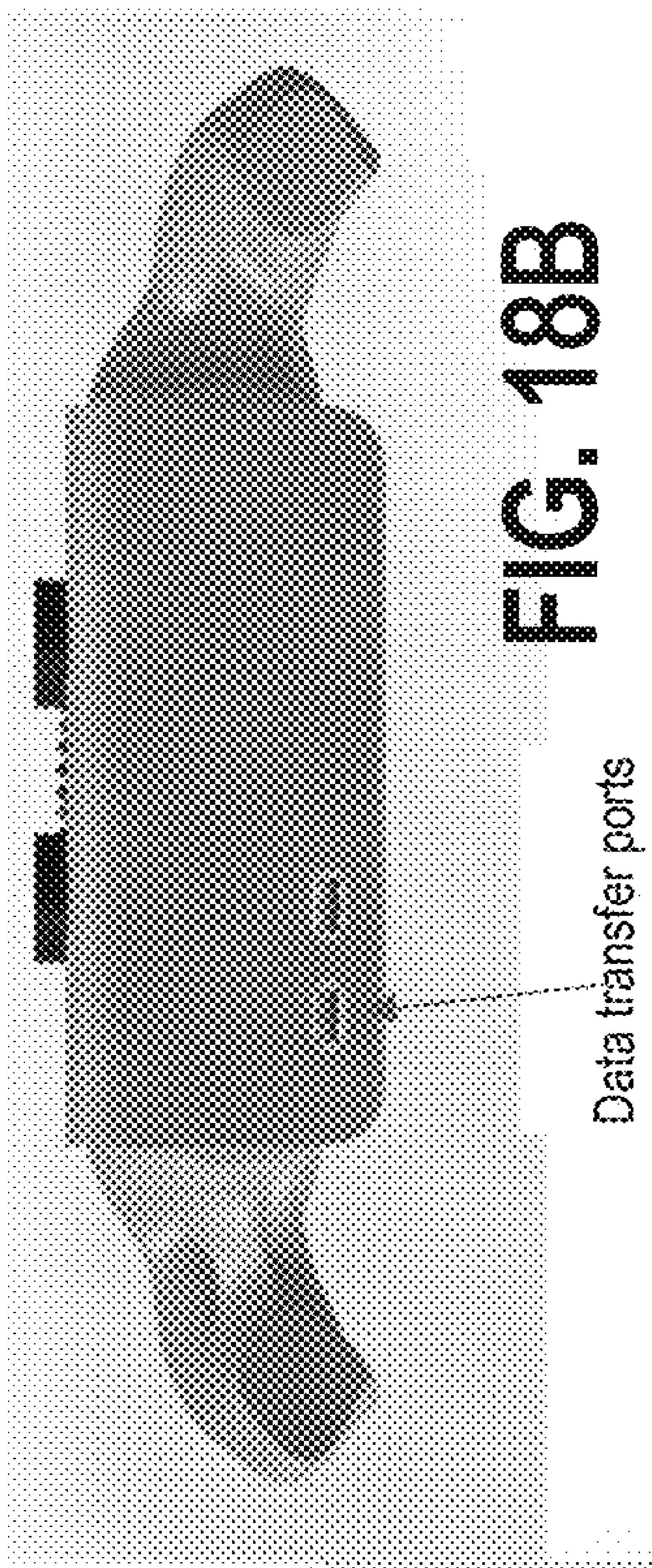

FIG. 18B

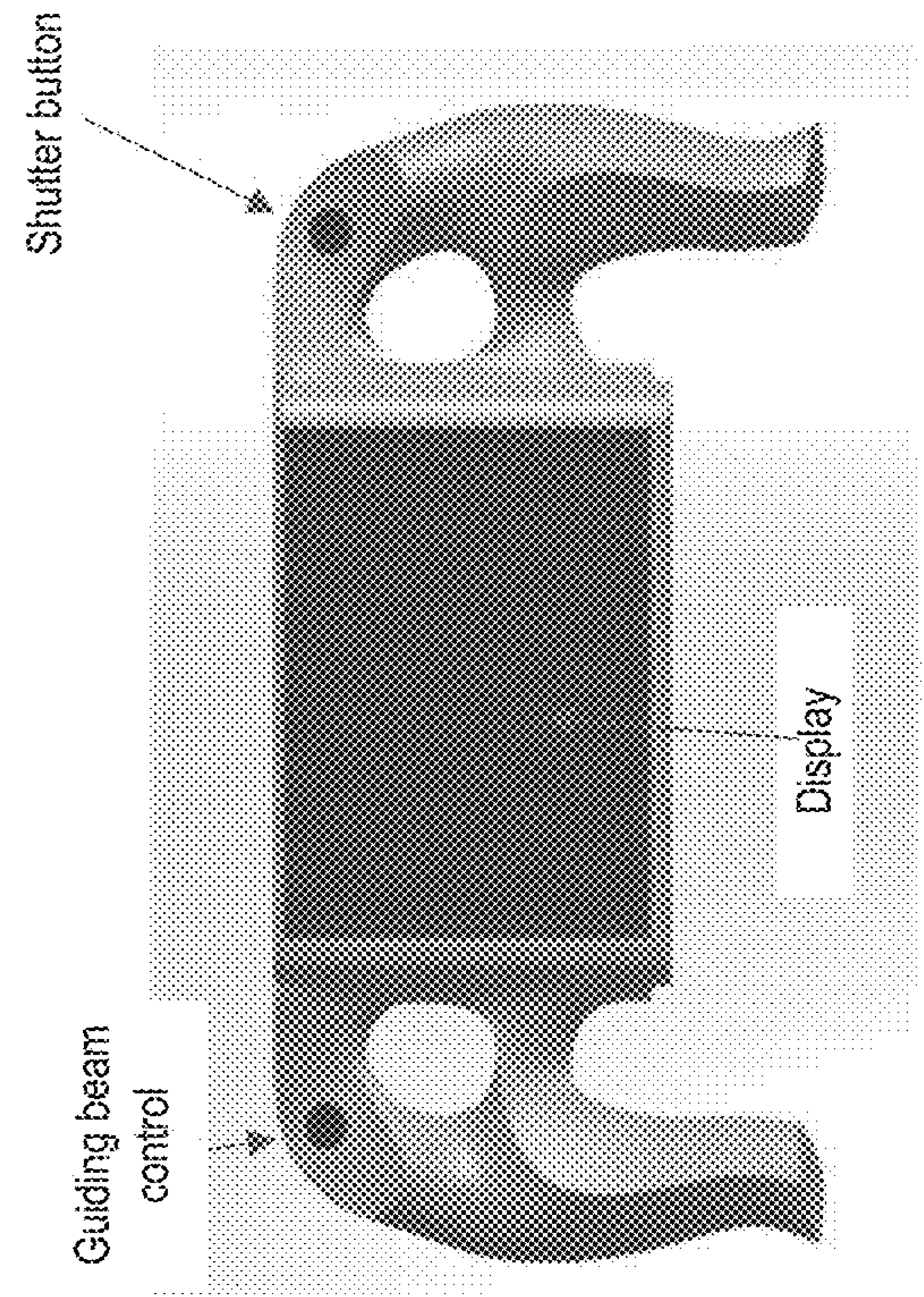

FIG. 18C

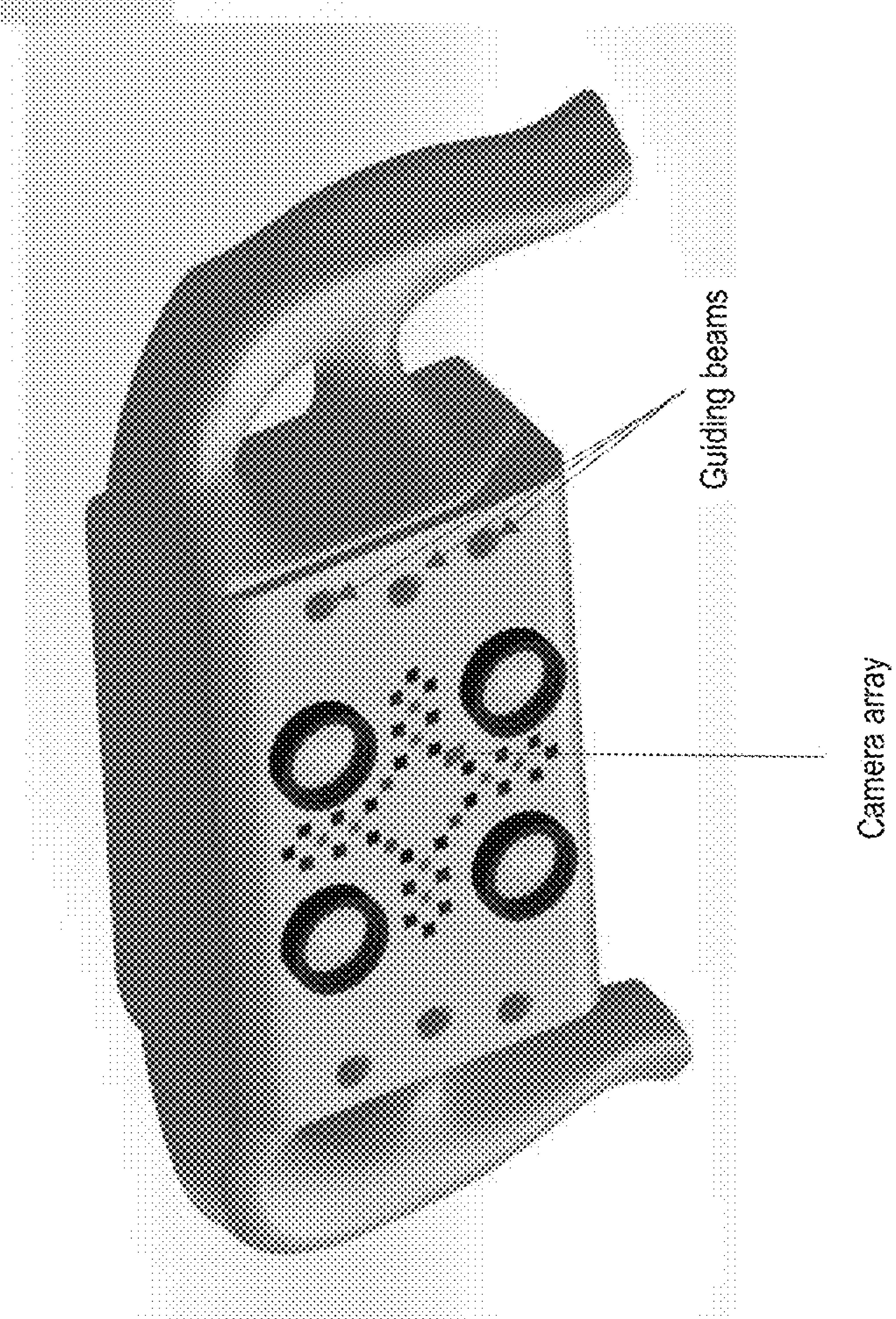

FIG. 18A

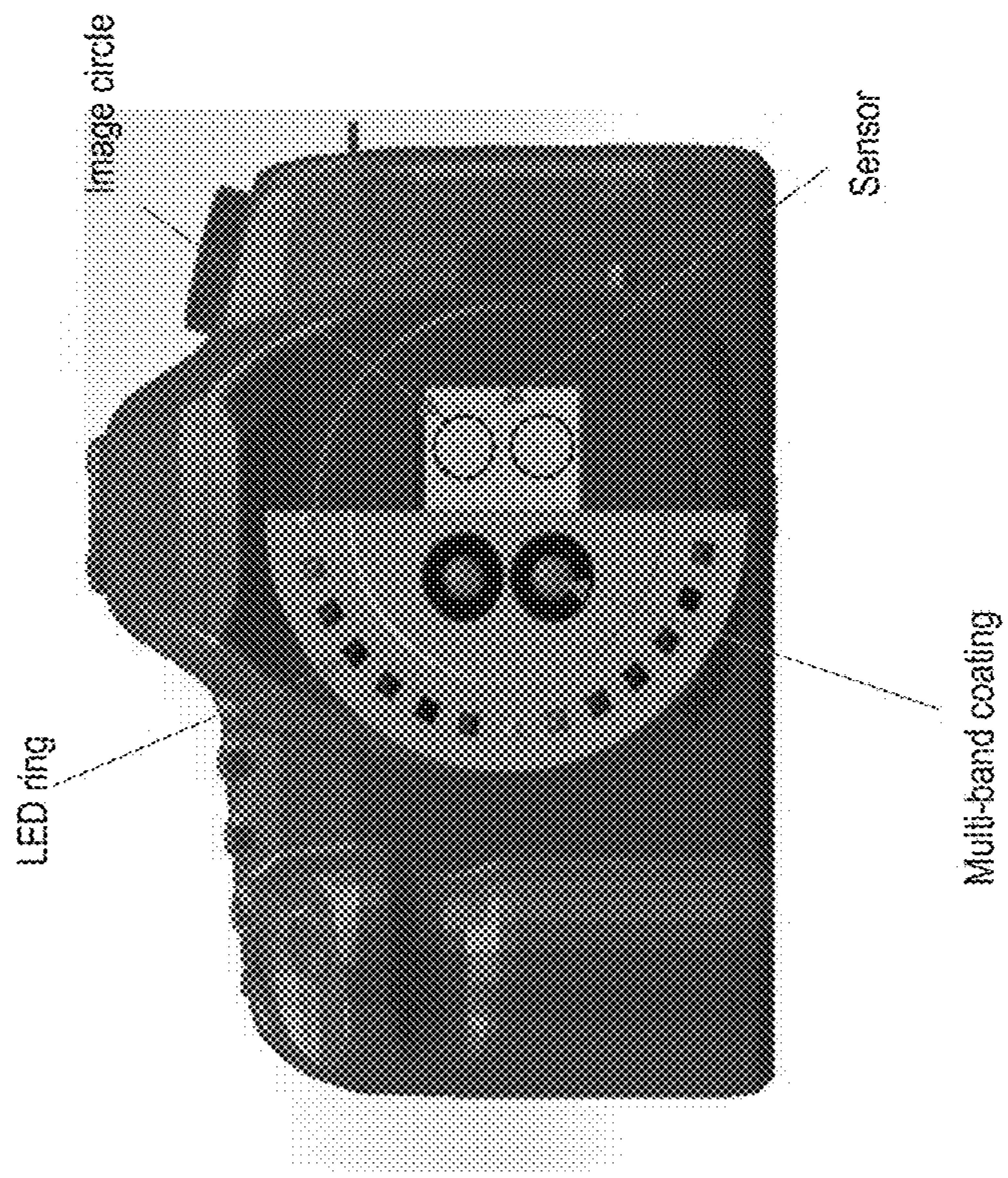

FIG. 19B

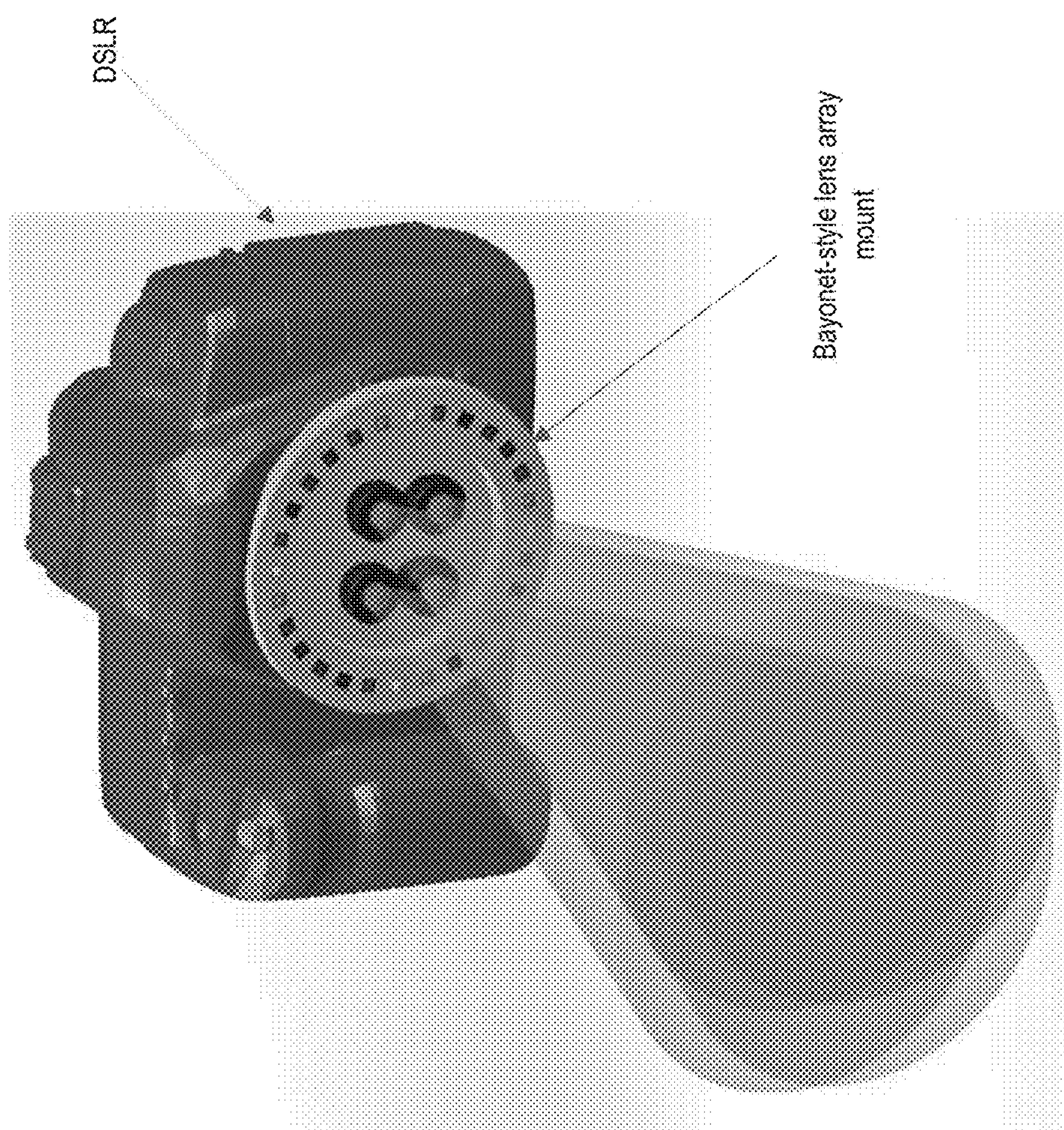

FIG. 19A

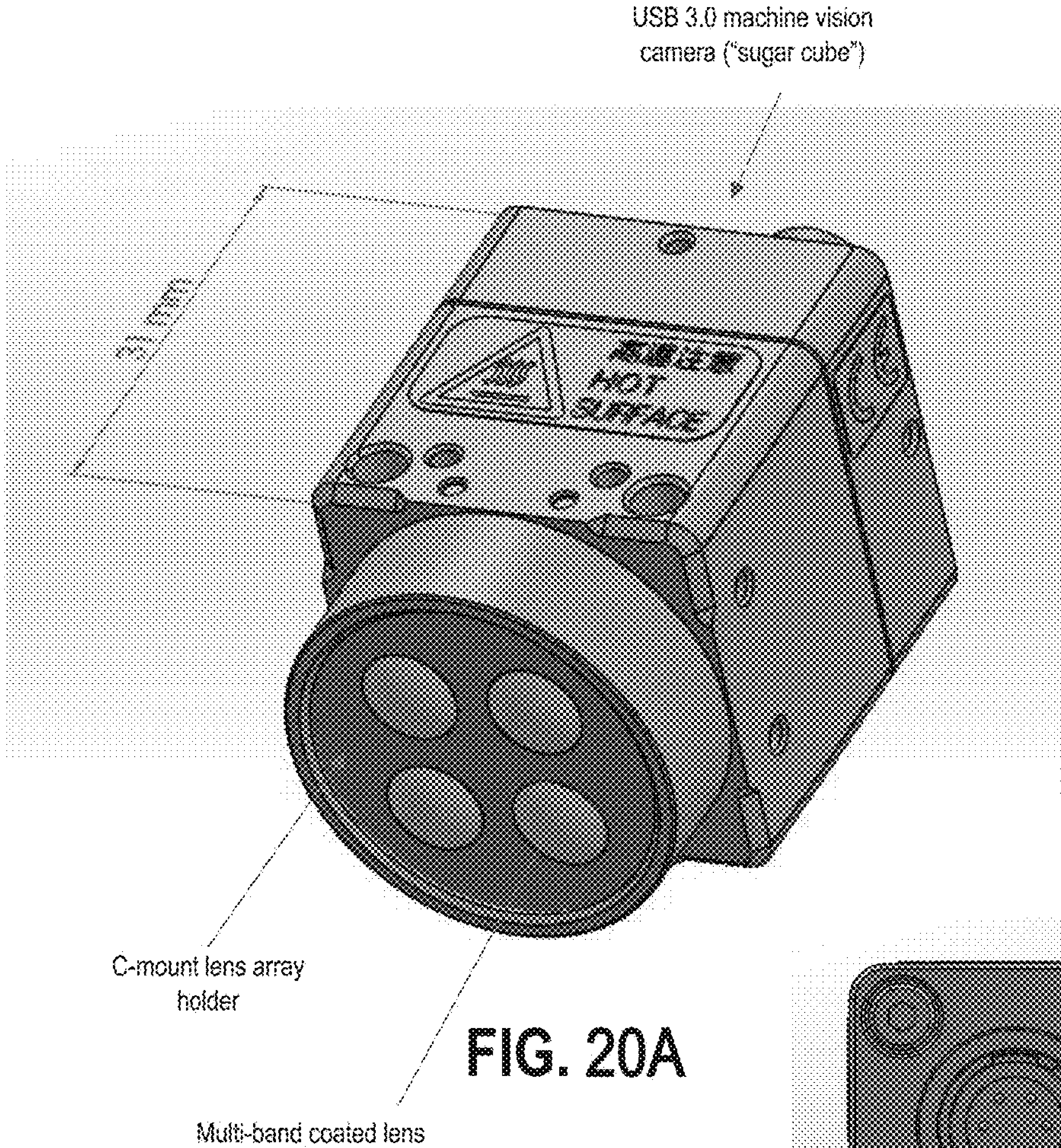

FIG. 20A

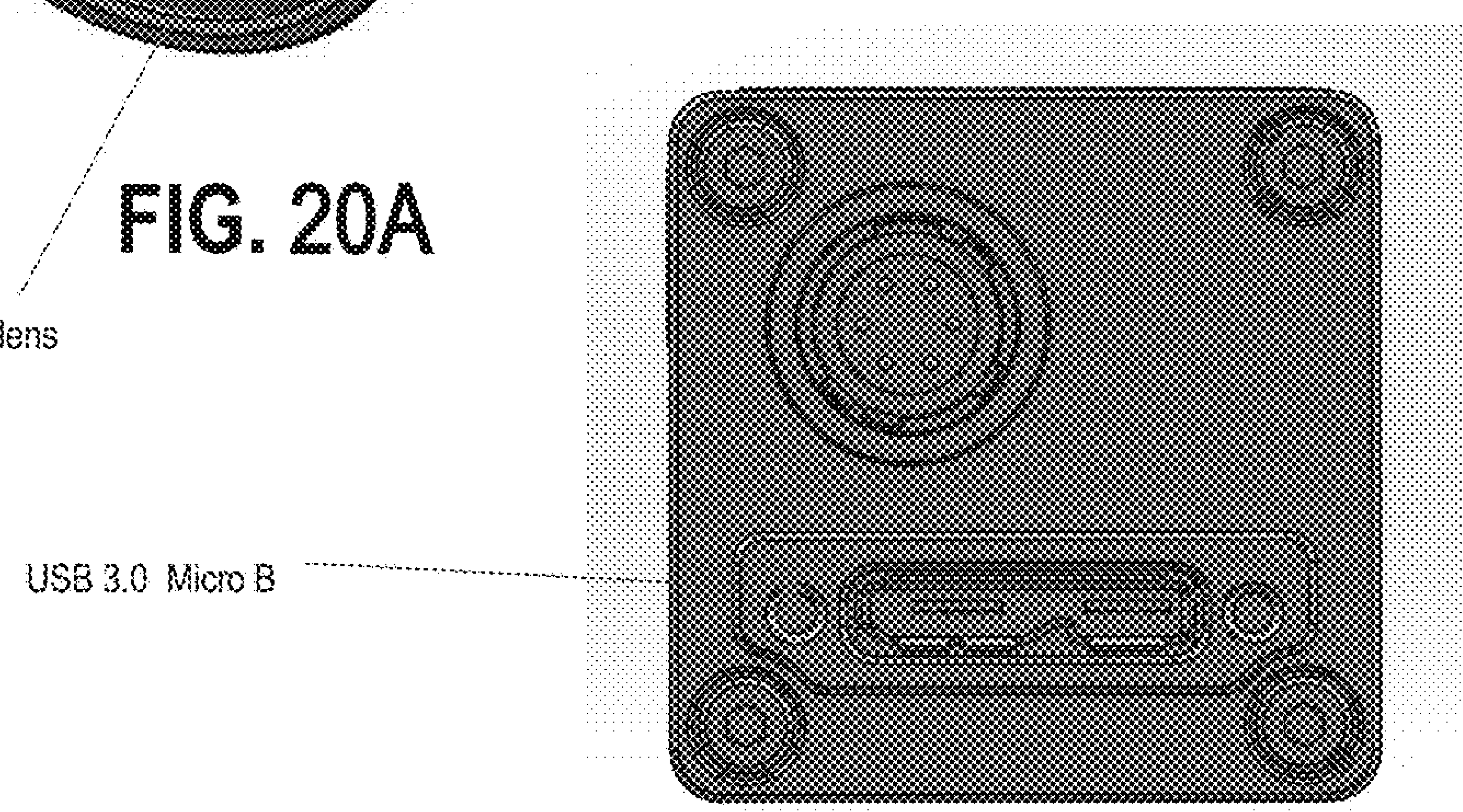

FIG. 20B

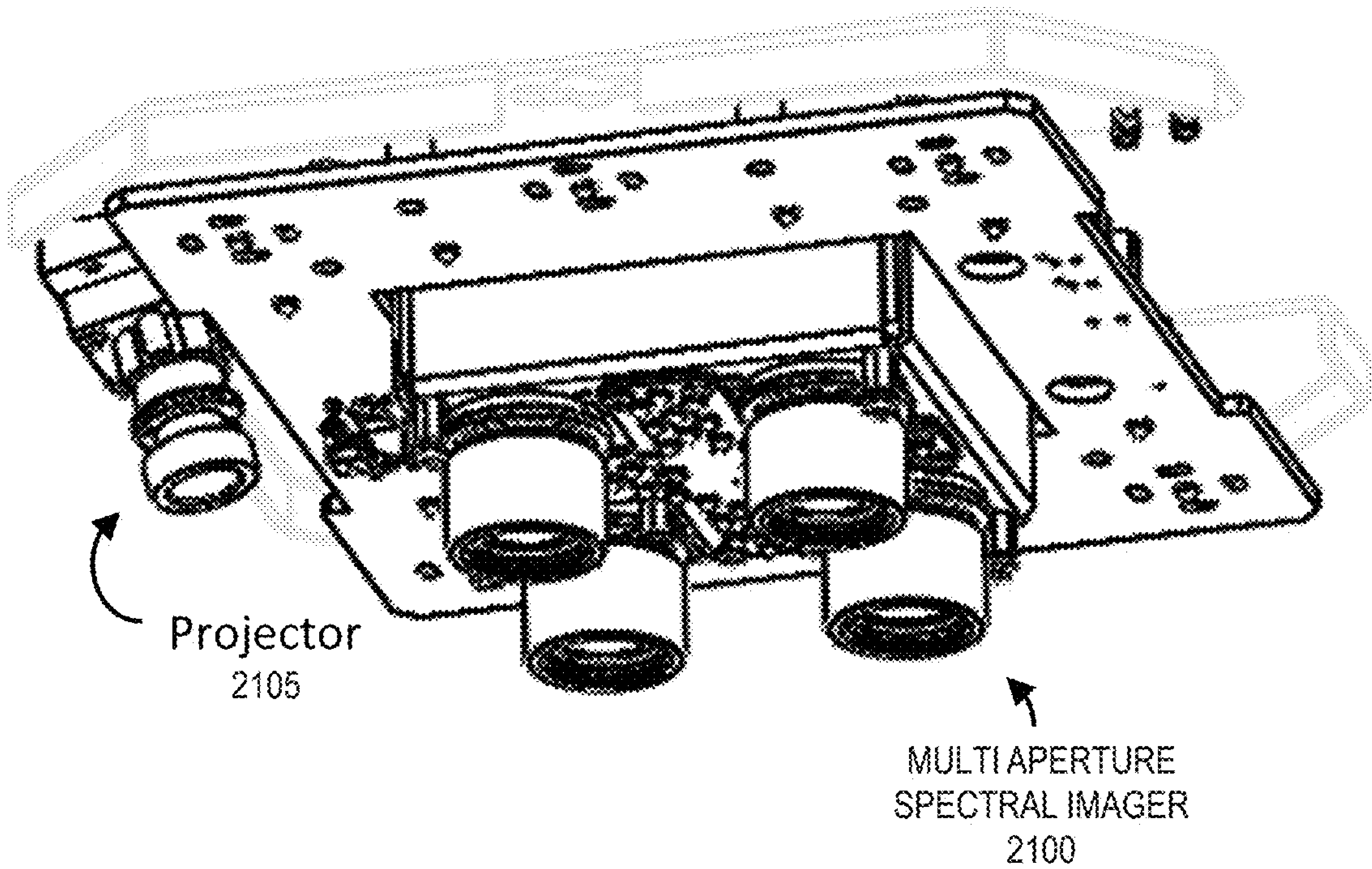

FIG. 21

SYSTEM AND METHOD FOR HIGH PRECISION MULTI-APERTURE SPECTRAL IMAGING

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of PCT/US2019/065818, filed Dec. 11, 2019, entitled "SYSTEM AND METHOD FOR HIGH PRECISION MULTI-APERTURE SPECTRAL IMAGING," which claims the benefit of U.S. Provisional Application Ser. No. 62/780,121 filed Dec. 14, 2018, entitled "SYSTEM AND METHOD FOR HIGH PRECISION MULTI-APERTURE SPECTRAL IMAGING," and U.S. Provisional Application Ser. No. 62/818,375, filed Mar. 14, 2019, entitled "SYSTEM AND METHOD FOR HIGH PRECISION MULTI-APERTURE SPECTRAL IMAGING," all of which are hereby expressly incorporated by reference in their entirety and for all purposes.

STATEMENT REGARDING FEDERALLY SPONSORED R&D

Some of the work described in this disclosure was made with United States Government support under Contract No. HHSO100201300022C, awarded by the Biomedical Advanced Research and Development Authority (BARDA), within the Office of the Assistant Secretary for Preparedness and Response in the U.S. Department of Health and Human Services. Some of the work described in this disclosure was made with United Government support under Contract Nos. W81XWH-17-C-0170 and/or W81XWH-18-C-0114, awarded by the U.S. Defense Health Agency (DHA). The United States Government may have certain rights in this invention.

TECHNICAL FIELD

The systems and methods disclosed herein are directed to spectral imaging, and, more particularly, to high precision spectral imaging via a multi-aperture imaging system.

BACKGROUND

The electromagnetic spectrum is the range of wavelengths or frequencies over which electromagnetic radiation (e.g., light) extends. In order from longer wavelengths to shorter wavelengths, the electromagnetic spectrum includes radio waves, microwaves, infrared (IR) light, visible light (that is, light that is detectable by the structures of the human eye), ultraviolet (UV) light, x-rays, and gamma rays. Spectral imaging refers to a branch of spectroscopy and photography in which some spectral information or a complete spectrum is collected at locations in an image plane. Multispectral imaging systems can capture multiple spectral bands (on the order of a dozen or less and typically at discrete spectral regions), for which spectral band measurements are collected at each pixel, and can refer to bandwidths of about tens of nanometers per spectral channel. Hyperspectral imaging systems measure a greater number of spectral bands, for example as many as 200 or more, with some providing a continuous sampling of narrow bands (e.g., spectral bandwidths on the order of nanometers or less) along a portion of the electromagnetic spectrum.

SUMMARY

The multispectral imaging systems and techniques disclosed herein have several features, no single one of which

is solely responsible for its desirable attributes. Without limiting the scope as expressed by the claims that follow, certain features of the disclosed spectral imaging will now be discussed briefly. One skilled in the art will understand how the features of the disclosed spectral imaging provide several advantages over traditional systems and methods.

One aspect relates to a multispectral image system comprising at least one image sensor; a first aperture positioned to allow incoming light to pass to a first sensor region of the at least one image sensor; a second aperture positioned to allow incoming light to pass to a second sensor region of the at least one image sensor; a first multi-bandpass filter positioned over the first aperture, wherein the first multi-bandpass filter is configured to allow passage of light in at least a common waveband and a first unique waveband; a second multi-bandpass filter positioned over the second aperture, wherein the second multi-bandpass filter is configured to allow passage of light in at least the common waveband and a second unique waveband; a memory storing instructions for generating a multispectral datacube; and at least one processor configured by the instructions to at least: receive signals from the first and second sensor regions; and process the signals to generate the multispectral datacube, wherein the multispectral datacube includes a first spectral channel corresponding to the common waveband, a second spectral channel corresponding to the first unique waveband, and a third spectral channel corresponding to the second unique waveband; wherein processing the signals comprises at least: estimating, using information from the first spectral channel corresponding to the common waveband, a disparity between first image data captured by the first sensor region and second image data captured by the second sensor region; and using the disparity to align the image data of the first, second, and third spectral channels to generate the multispectral datacube.

In some embodiments, the first multi-bandpass filter is positioned in front of a lens of the multispectral image system, behind a lens of the multispectral image system, inside a lens of the multispectral image system, or directly onto a surface of an element of a lens of the multispectral image system. In some embodiments, the at least one processor is configured by the instructions to at least perform spectral unmixing to generate image data for each of the first, second, and third spectral channels. In some embodiments, the multispectral image system further comprises a color filter array covering the first and second sensor regions, the color filter array including a repeating pattern of color filters; wherein a first color filter of the repeating pattern is configured to pass a first weighted distribution of wavelengths of light including the common waveband; wherein a second color filter of the repeating pattern is configured to pass a second weighted distribution of wavelengths of light including the first unique waveband; and wherein a third color filter of the repeating pattern is configured to pass a third weighted distribution of wavelengths of light including the second unique waveband. In some embodiments, the common waveband comprises at least one of violet, violet-blue, blue, or blue-green light. In some embodiments, the common waveband comprises light having a wavelength shorter than 450 nm and longer than 380 nm. In some embodiments, the common waveband comprises green light. In some embodiments, the common waveband comprises red light. In some embodiments, the first and second multi-bandpass filters are each configured to pass a second common waveband comprising at least one of green, blue-green, or blue light. In some embodiments, the first and second multi-bandpass filters are each configured to

pass a second common waveband comprising red light. In some embodiments, the first and second multi-bandpass filters are each configured to pass a second common waveband that is unfiltered by at least one of the color filters patterned in the color filter array that also does not filter the first common waveband. In some embodiments, the at least one processor is configured by the instructions to at least perform spectral unmixing to isolate portions of captured image data corresponding to the common waveband and the second common waveband. In some embodiments, the at least one processor is configured by the instructions to at least analyze imaged tissue using the multispectral datacube.

In some embodiments, the multispectral image system further comprises a third aperture positioned to allow incoming light to pass to a third sensor region of the at least one image sensor; a fourth aperture positioned to allow incoming light to pass to a fourth sensor region of the at least one image sensor; a third multi-bandpass filter positioned over the third aperture, wherein the third multi-bandpass filter is configured to allow passage of light in at least a common waveband and a third unique waveband; and a fourth multi-bandpass filter positioned over the fourth aperture, wherein the fourth multi-bandpass filter is configured to allow passage of light in at least the common waveband and a fourth unique waveband. In some embodiments, the multispectral image system further comprises a fifth aperture positioned to allow incoming light to pass to a fifth sensor region of the at least one image sensor; and a fifth multi-bandpass filter positioned over the third aperture, wherein the fifth multi-bandpass filter is configured to allow passage of light in at least one waveband passed by at least one of the first multi-bandpass filter, the second multi-bandpass filter, the third multi-bandpass filter, or the fourth multi-bandpass filter. In some embodiments, the multispectral image system comprises: up to 25 total apertures positioned to allow incoming light to pass and up to 25 total sensor regions of the at least one image sensor; and up to 25 multi-bandpass filters each positioned over one of the 25 total apertures, wherein each multi-bandpass filter is configured to allow passage of light in at least a common waveband and a unique waveband for which none of the other multi-bandpass filters are configured to allow passage; wherein the total number of wavebands that are allowed to pass is more than four and less than 51. In some embodiments, the multispectral image system further comprises a third aperture positioned to allow incoming light to pass to a third sensor region of the at least one image sensor; and a third multi-bandpass filter positioned over the third aperture, wherein the third multi-bandpass filter is configured to allow passage of light in at least one waveband passed by at least one of the first multi-bandpass filter or the second multi-bandpass filter. In some embodiments, the first, second, third, and fourth multi-bandpass filters collectively pass seven, eight, nine, or ten distinct wavebands including the common waveband and the first, second, third, and fourth unique wavebands. In some embodiments, the first, second, third, and fourth multi-bandpass filters are each configured to pass the common waveband comprising blue light, an additional common waveband comprising green light, and two additional wavebands. In some embodiments, the at least one processor is configured by the instructions to at least generate the multispectral datacube to include ten spectral channels corresponding to the seven, eight, nine, or ten distinct wavebands.

In some embodiments, the multispectral image system further comprises an illumination board comprising a plurality of light-emitting diodes (LEDs) configured to emit light in the seven, eight, nine, or ten distinct wavebands, wherein individual LEDs emit light at a particular one of the seven, eight, nine, orten distinct wavebands. In some embodiments, the at least one image sensor comprises a color filter array positioned over photodiodes of the at least one image sensor, and wherein the color filter array has at least two different color filters. In some embodiments, the color filter array has more than two different color filters and not more than 25 different color filters. In some embodiments, the seven, eight, nine, or ten distinct wavebands comprises narrower ranges of light than are passed by the three different color filters. In some embodiments, the multispectral image system further comprises at least one light source configured to emit light at the common waveband, the first unique waveband, and the second unique waveband. In some embodiments, the multispectral image system further comprises a diffusing optical element positioned over the at least one light source. In some embodiments, at least the first multi-bandpass filter is a curved filter.

Another aspect relates to a method of using any one of the multispectral image systems described herein to generate the multispectral datacube, the method comprising capturing a first exposure comprising the first, second, and third spectral channels; capturing a second exposure comprising the first, second, and third spectral channels; and generating the multispectral datacube based at least partly on using the second exposure to reduce a signal to noise ratio of the first exposure. In some embodiments, the method further comprises activating a set of illuminants that collectively emit light at the common waveband, the first unique waveband, and the second unique waveband during the first and second exposures. In some embodiments, the first exposure and the second exposure each comprise at least a fourth spectral channel and not more than ten total spectral channels. In some embodiments, the method further comprises capturing a third exposure using ambient light; and subtracting the third exposure from the first and second exposures. In some embodiments, the method further comprises generating the multispectral datacube based on a result of subtracting the third exposure from the first and second exposures. In some embodiments, the method further comprises registering images captured by the first and second sensor regions to one another based on information in the first spectral channel. In some embodiments, the method further comprises generating the multispectral datacube based on a result of registering the images captured by the first and second sensor regions to one another. In some embodiments, the images represent information captured in the first spectral channel by the first and second sensor regions, the method further comprising identifying a disparity between the images captured by the first and second sensor regions in the first spectral channel corresponding to the common waveband; using the disparity to register a first additional image to the images, the first additional image representing information captured by the first sensor region in the second spectral channel; and using the disparity to register a second additional image to the images, the second additional image representing information captured by the second sensor region in the third spectral channel. In some embodiments, each exposure comprises more than three spectral channels, the method further comprising using the disparity to register at least a third additional image to the images, the third additional image representing information captured by a third sensor region in the fourth spectral channel, wherein a total number of additional images registered to the images is one less than the total number of spectral channels. In some embodiments, the multispectral image system further comprises an illuminant configured to project one or more points, fringes, grids, random speckle, or other spatial pattern, the method further comprising projecting, by the illuminant into the field of view of the at least one imaging sensor, light comprising one or more points, fringes, grids, random speckle, or other spatial pattern; and capturing an additional exposure using the light projected by the illuminant, wherein the registering is based at least in part on the additional exposure. In some embodiments, the light projected by the illuminant comprises at least one of light having a wavelength in the common waveband, broadband illumination, or cumulatively visible illumination. In some embodiments, the additional exposure is used to confirm the accuracy of the registration of the image. In some embodiments, the additional exposure is included in the calculation of the disparity to improve the accuracy of the registration. In some embodiments, the illuminant projects a plurality of points, fringes, grids, random speckle, or other spatial patterns in unique configurations in at least the common waveband, broadband illumination, or cumulatively visible illumination to further improve the accuracy of the registering. In some embodiments, the multispectral image system further comprises an additional sensor configured to detect the shape of objects in the field of view of the at least one imaging sensor, and the registering is based at least in part on a shape detected by the additional sensor. This additional sensor may be a single-aperture sensor or a multi-aperture sensor, sensitive to light-field information, or it may be sensitive to other signals, such as ultrasound or pulsed lasers. In some embodiments, the method further comprises performing spectral unmixing to isolate the first, second, and third spectral channels. In some embodiments, each exposure comprises more than three spectral channels, the method further comprising performing spectral unmixing to isolate all of the spectral channels. In some embodiments, the method further comprises using the disparity to determine at least one of topographic information or depth information. In some embodiments, the disparity is used to determine depth information for individual pixels. In some embodiments, the method further comprises using the depth information to determine a volume of an imaged wound. In some embodiments, the method further comprises capturing an additional exposure comprising at least a fourth spectral channel representing non-visible light; and generating the multispectral datacube based at least partly on the additional exposure. In some embodiments, the method further comprises activating a third set of illuminants that emit the non-visible light during the additional exposure.

Another aspect relates to a method of automated tissue analysis, the method comprising using any one of the multispectral image systems described herein to generate the multispectral datacube representing imaged tissue; providing the multispectral datacube as input to a machine learning system trained to predict at least one clinical characteristic of tissue; and predicting the at least one clinical characteristic of the imaged tissue based on an output of the machine learning system.

In some embodiments, the method further comprises generating the multispectral datacube using the multispectral datacube generation methods described herein. In some embodiments, the at least one clinical characteristic includes a plurality of wound states or burn states, the method further comprising using the output of the machine learning system to generate a classified image of the imaged tissue showing areas of the imaged tissue classified into different ones of the plurality of wound states or burn states. In some embodiments, for example, the plurality of burn states include at least first degree burn, second degree burn, third degree burn, or healthy skin categories, the method further comprising classifying each of a plurality of pixels depicting the imaged tissue as one of the first degree burn, second degree burn, third degree burn, or healthy skin categories. In some embodiments, for example, the plurality of wound states include at least hemostasis, inflammation, proliferation, remodeling or healthy skin categories, the method further comprising classifying each of a plurality of pixels depicting the imaged tissue as one of the hemostasis, inflammation, proliferation, remodeling or healthy skin categories. In some embodiments, the at least one clinical characteristic includes a healing potential, the method further comprising using the output of the machine learning system to generate an image of the imaged tissue that visually depicts determined healing potential at different areas of the imaged tissue. In some embodiments, the at least one clinical characteristic includes a cancerous or non-cancerous state of the imaged tissue, the method further comprising classifying each of a plurality of pixels depicting the imaged tissue as either the cancerous or non-cancerous state. In some embodiments, the at least one clinical characteristic includes wound depth, the method further comprising outputting information identifying a depth of a wound in the imaged tissue. In some embodiments, the at least one clinical characteristic includes a margin for debridement, the method further comprising outputting information identifying the margin for debridement in or around a wound in the imaged tissue. In some embodiments, the at least one clinical characteristic includes a diabetic, non-diabetic, or chronic ulcer. In some embodiments, the at least one clinical characteristic includes a diabetic foot ulcer.

Another aspect relates to a method of automated biometric recognition, the method comprising using any one of the multispectral image systems described herein to generate the multispectral datacube representing a biometric feature of a user; providing the multispectral datacube as input to a machine learning system trained to authenticate a particular biometric feature; and authenticating or rejecting the user based on an output of the machine learning system.

In some embodiments, the method further comprises generating the multispectral datacube using any one of the multispectral datacube generation methods described herein.

Another aspect relates to a method of automated materials analysis, the method comprising using any one of the multispectral image systems described herein to generate the multispectral datacube representing an imaged material; providing the multispectral datacube as input to a machine learning system trained to determine one or more materials characteristics; and determining the one or more materials characteristics of the imaged material based on an output of the machine learning system.

In some embodiments, the method further comprises generating the multispectral datacube using any one of the multispectral datacube generation methods described herein.

Another aspect relates to a method comprising capturing image information using a multi-aperture handheld imaging device comprising at least one image sensor region having a color filter array, wherein the image information includes a greater number of channels than a number of color filter colors in the color filter array; and processing the image information into a multispectral datacube including the number of channels, wherein the each of number of channels represents light in a different waveband spanning approximately 40 nm or less, but not zero.

In some embodiments, the multi-aperture handheld imaging device comprises any one of the multispectral image systems described herein. In some embodiments, the method further comprises generating the multispectral datacube using the method of any one of the multispectral datacube generation methods described herein.

Another aspect relates to a method comprising using any one of the multispectral image systems described herein generate the multispectral datacube; and processing the multispectral datacube using the at least one processor of the multispectral image system to determine at least one characteristic of an object represented by the multispectral datacube.

In some embodiments, further comprises generating the multispectral datacube using any one of the multispectral datacube generation methods described herein.

Another aspect relates to a method comprising using any one of the multispectral image systems described herein to generate the multispectral datacube; transmitting the multispectral datacube to at least one remote processor over a network; and processing the multispectral datacube using the at least remote one processor to determine at least one characteristic of an object represented by the multispectral datacube. In some embodiments, the method further comprises generating the multispectral datacube using any one of the multispectral datacube generation methods described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**A illustrates an example of light incident on a filter at different chief ray angles.

FIG. **1**B is a graph illustrating example transmission efficiencies provided by the filter of FIG. **1**A for various chief ray angles.

FIG. **2**A illustrates an example of a multispectral image datacube.

FIG. **2**B illustrates examples of how certain multispectral imaging technologies generate the datacube of FIG. **2**A.

FIG. **2**C depicts an example snapshot imaging system that can generate the datacube of FIG. **2**A.

FIG. **3**A depicts a schematic cross-sectional view of an optical design of an example multi-aperture imaging system with curved multi-bandpass filters, according to the present disclosure.

FIGS. **3**B-**3**D depict example optical designs for optical components of one light path of the multi-aperture imaging system of FIG. **3**A.

FIGS. **4**A-**4**E depict an embodiment of a multispectral multi-aperture imaging system, with an optical design as described with respect to FIGS. **3**A and **3**B.

FIG. **5** depicts another embodiment of a multispectral multi-aperture imaging system, with an optical design as described with respect to FIGS. **3**A and **3**B.

FIGS. **6**A-**6**C depict another embodiment of a multispectral multi-aperture imaging system, with an optical design as described with respect to FIGS. **3**A and **3**B.

FIGS. **7**A-**7**B depict another embodiment of a multispectral multi-aperture imaging system, with an optical design as described with respect to FIGS. **3**A and **3**B.

FIGS. **8**A-**8**B depict another embodiment of a multispectral multi-aperture imaging system, with an optical design as described with respect to FIGS. **3**A and **3**B.

FIGS. **9**A-**9**C depict another embodiment of a multispectral multi-aperture imaging system, with an optical design as described with respect to FIGS. **3**A and **3**B.

FIGS. **10**A-**10**B depict another embodiment of a multispectral multi-aperture imaging system, with an optical design as described with respect to FIGS. **3**A and **3**B.

FIGS. **11**A-**11**B depict an example set of wavebands that can be passed by the filters of the multispectral multi-aperture imaging systems of FIGS. **3**A-**10**B.

FIG. **12** depicts a schematic block diagram of an imaging system that can be used for the multispectral multi-aperture imaging systems of FIGS. **3**A-**10**B.

FIG. **13** is a flowchart of an example process for capturing image data using the multispectral multi-aperture imaging systems of FIGS. **3**A-**10**B.

FIG. **14** depicts a schematic block diagram of a workflow for processing image data, for example image data captured using the process of FIG. **13** and/or using the multispectral multi-aperture imaging systems of FIGS. **3**A-**10**B.

FIG. **15** graphically depicts disparity and disparity correction for processing image data, for example image data captured using the process of FIG. **13** and/or using the multispectral multi-aperture imaging systems of FIGS. **3**A-**10**B.

FIG. **16** graphically depicts a workflow for performing pixel-wise classification on multispectral image data, for example image data captured using the process of FIG. **13**, processed according to FIGS. **14** and **15**, and/or using the multispectral multi-aperture imaging systems of FIGS. **3**A-**10**B.

FIG. **17** depicts a schematic block diagram of an example distributed computing system including the multispectral multi-aperture imaging systems of FIGS. **3**A-**10**B.

FIGS. **18**A-**18**C illustrate an example handheld embodiment of a multi spectral, multi-aperture imaging system.

FIGS. **19**A and **19**B illustrate an example handheld embodiment of a multi spectral, multi-aperture imaging system.

FIGS. **20**A and **20**B illustrate an example multispectral, multi-aperture imaging system for a small USB 3.0 enclosed in a common camera housing.

FIG. **21** illustrates an example multispectral, multi-aperture imaging system including an additional illuminant for improved image registration.

DETAILED DESCRIPTION

Generally described, the present disclosure relates to spectral imaging using a multi-aperture system with curved multi-bandpass filters positioned over each aperture. The present disclosure further relates to techniques for implementing spectral unmixing and image registration to generate a spectral datacube using image information received from such imaging systems. The disclosed technology addresses a number of challenges that are typically present in spectral imaging, described below, in order to yield image data that represents precise information about wavelength bands that were reflected from an imaged object. In some embodiments, the systems and methods described herein acquire images from a wide area of tissue (e.g., 5.9×7.9 inches) in a short amount of time (e.g., within 6 seconds or less) and can do so without requiring the injection of imaging contrast agents. In some aspects, for example, the multispectral image system described herein is configured to acquire images from a wide area of tissue, e.g., 5.9×7.9 inches, within 6 seconds or less and, wherein said multispectral image system is also configured to provide tissue analysis information, such as identification of a plurality of burn states, wound states, healing potential, a clinical characteristic including a cancerous or non-cancerous state of the imaged tissue, wound depth, a margin for debridement, or the presence of a diabetic, non-diabetic, or chronic ulcer in the absence of imaging contrast agents. Similarly, in some of the methods described herein, the multispectral image system acquires images from a wide area of tissue, e.g., 5.9×7.9 inches, within 6 seconds or less and said multispectral image system outputs tissue analysis information, such as identification of a plurality of burn states, wound states, healing potential, a clinical characteristic including a cancerous or non-cancerous state of the imaged tissue, wound depth, a margin for debridement, or the presence of a diabetic, non-diabetic, or chronic ulcer in the absence of imaging contrast agents.

One such challenge in existing solutions is that captured images can suffer from color distortions that compromise the quality of the image data. This can be particularly problematic for applications that depend upon precise detection and analysis of certain wavelengths of light using optical filters. Specifically, color shading is a position dependent variation in the wavelength of light across the area of the image sensor, due to the fact that transmittance of a color filter shifts to shorter wavelengths as the angle of light incident on the filter increases. Typically, this effect is observed in interference-based filters, which are manufactured through the deposition of thin layers with varying refractive indices onto a transparent substrate. Accordingly, longer wavelengths (such as red light) can be blocked more at the edges of the image sensor due to larger incident light ray angles, resulting in the same incoming wavelength of light being detected as a spatially non-uniform color across the image sensor. If left uncorrected, color shading manifests as shift in color near the edges of the captured image.

The technology of the present disclosure provides advantages relative to other multi-spectral imaging systems on the market because it is not restrictive in the configuration of lens and/or image sensors and their respective fields of view or aperture sizes. It will be understood that changes to lenses, image sensors, aperture sizes, or other components of the presently disclosed imaging systems may involve other adjustments to the imaging system as would be known to those of ordinary skill in the art. The technology of the present disclosure also provides improvements over other multi-spectral imaging systems in that the components that perform the function of resolving wavelengths or causing the system as a whole to be able to resolve wavelengths (e.g., optical filters or the like) can be separable from the components that transduce light energy into digital outputs (e.g., image sensors or the like). This reduces the cost, complexity, and/or development time to re-configure imaging systems for different multi-spectral wavelengths. The technology of the present disclosure may be more robust than other multi-spectral imaging systems in that it can accomplish the same imaging characteristics as other multi-spectral imaging systems on the market in a smaller and lighter form factor. The technology of the present disclosure is also advantageous relative to other multi-spectral imaging systems in that it can acquire multi-spectral images in a snapshot, video rate, or high speed video rate. The technology of the present disclosure also provides a more robust implementation of multi-spectral imaging systems based on multi-aperture technology as the ability to multiplex several spectral bands into each aperture reduces the number of apertures necessary to acquire any particular number of spectral bands in an imaging data set, thus reducing costs through a reduced number of apertures and improved light collection (e.g., as larger apertures may be used within the fixed size and dimensions of commercially available sensor arrays). Finally, the technology of the present disclosure can provide all of these advantages without a trade-off with respect to resolution or image quality.

FIG. **1**A illustrates an example of a filter **108** positioned along the path of light towards an image sensor **110**, and also illustrates light incident on the filter **108** at different ray angles. The rays **102**A, **104**A, **106**A are represented as lines which, after passing through the filter **108**, are refracted onto the sensor **110** by a lens **112**, which may also be substituted with any other image-forming optics, including but not limited to a mirror and/or an aperture. The light for each ray is presumed in FIG. **1**A to be broadband, for example, having a spectral composition extending over a large wavelength range to be selectively filtered by filter **108**. The three rays **102**A, **104**A, **106**A each arrive at the filter **108** at a different angle. For illustrative purposes, light ray **102**A is shown as being incident substantially normal to filter **108**, light ray **104**A has a greater angle of incidence than light ray **102**A, and light ray **106**A has a greater angle of incidence than light ray **104**A. The resulting filtered rays **102**B, **104**B, **106**B exhibit a unique spectrum due to the angular dependence of the transmittance properties of the filter **108** as seen by the sensor **110**. The effect of this dependence causes a shift in the bandpass of the filter **108** towards shorter wavelengths as the angle of incidence increases. Additionally, the dependence may cause a reduction in the transmission efficiency of the filter **108** and an altering of the spectral shape of the bandpass of the filter **108**. These combined effects are referred to as the angular-dependent spectral transmission. FIG. **1**B depicts the spectrum of each light ray in FIG. **1**A as seen by a hypothetical spectrometer at the location of sensor **110** to illustrate the shifting of the spectral bandpass of filter **108** in response to increasing angle of incidence. The curves **102**C, **104**C, and **106**C demonstrate the shortening of the center wavelength of the bandpass; hence, the shortening of the wavelengths of light passed by the optical system in the example. Also shown, the shape of the bandpass and the peak transmission are altered due to the angle incidence as well. For certain consumer applications, image processing can be applied to remove the visible effects of this angular-dependent spectral transmission. However, these post-processing techniques do not allow for recovery of precise information regarding which wavelength of light was actually incident upon the filter **108**. Accordingly, the resulting image data may be unusable for certain high-precision applications.

Another challenge faced by certain existing spectral imaging systems is the time required for capture of a complete set of spectral image data, as discussed in connection with FIGS. **2**A and **2**B. Spectral imaging sensors sample the spectral irradiance $I(x,y,\lambda)$ of a scene and thus collect a three-dimensional (3D) dataset typically called a datacube. FIG. **2**A illustrates an example of a spectral image datacube **120**. As illustrated, the datacube **120** represents three dimensions of image data: two spatial dimensions (x and y) corresponding to the two-dimensional (2D) surface of the image sensor, and a spectral dimension (λ) corresponding to a particular wavelength band. The dimensions of the datacube **120** can be given by $N_xN_yN_\lambda$, where N_x, N_y, and N_λ are the number of sample elements along the (x, y) spatial dimensions and spectral axes λ, respectively. Because datacubes are of a higher dimensionality than 2D detector arrays (e.g., image sensors) that are currently available, typical spectral imaging systems either capture time-sequential 2D slices, or planes, of the datacube **120** (referred to herein as "scanning" imaging systems), or simultaneously measure all elements of the datacube by dividing it into multiple 2D elements that can be recombined into datacube **120** in processing (referred to herein as "snapshot" imaging systems).

FIG. **2**B illustrates examples of how certain scanning spectral imaging technologies generate the datacube **120**. Specifically, FIG. **2**B illustrates the portions **132**, **134**, and **136** of the datacube **120** that can be collected during a single detector integration period. A point scanning spectrometer, for example, can capture a portion **132** that extends across all spectral planes λ at a single (x, y) spatial position. A point scanning spectrometer can be used to build the datacube **120** by performing a number of integrations corresponding to each (x, y) position across the spatial dimensions. A filter wheel imaging system, for example, can capture a portion **134** that extends across the entirety of both spatial dimensions x and y, but only a single spectral plane λ. A wavelength scanning imaging system, such as a filter wheel imaging system, can be used to build the datacube **120** by performing a number of integrations corresponding to the number of spectral planes λ. A line scanning spectrometer, for example, can capture a portion **136** that extends across all spectral dimensions λ and all of one of the spatial dimension (x or y), but only a single point along the other spatial dimension (y or x). A line scanning spectrometer can be used to build the datacube **120** by performing a number of integrations corresponding to each position of this other spatial dimension (y or x).

For applications in which the target object and imaging system are both motionless (or remain relatively still over the exposure times), such scanning imaging systems provide the benefit of yielding a high resolution datacube **120**. For line scanning and wavelength scanning imaging systems, this can be due to the fact that each spectral or spatial image is captured using the entire area of the image sensor. However, movement of the imaging system and/or object between exposures can cause artifacts in the resulting image data. For example, the same (x, y) position in the datacube **120** can actually represent a different physical location on the imaged object across the spectral dimension λ. This can lead to errors in downstream analysis and/or impose an additional requirement for performing registration (e.g., aligning the spectral dimension λ so that a particular (x, y) position corresponds to the same physical location on the object).

In comparison, a snapshot imaging system **140** can capture an entire datacube **120** in a single integration period or exposure, thereby avoiding such motion-induced image quality issues. FIG. **2**C depicts an example image sensor **142** and an optical filter array such as a color filter array (CFA) **144** that can be used to create a snapshot imaging system. The CFA **144** in this example is a repeating pattern of color filter units **146** across the surface of the image sensor **142**. This method of acquiring spectral information can also be referred to as a multispectral filter array (MSFA) or a spectrally resolved detector array (SRDA). In the illustrated example, the color filter unit **146** includes a 5×5 arrangement of different color filters, which would generate 25 spectral channels in the resulting image data. By way of these different color filters, the CFA can split incoming light into the bands of the filters, and direct the split light to dedicated photoreceptors on the image sensor. In this way, for a given color **148**, only $1/25^{th}$ of the photoreceptors actually detect a signal represent light of that wavelength. Thus, although 25 different color channels can be generated in a single exposure with this snapshot imaging system **140**, each color channel represents a smaller quantity of measured data than the total output of the sensor **142**. In some embodiments, a CFA may include one or more of a filter array (MSFA), a spectrally resolved detector array (SRDA), and/or may include a conventional Bayer filter, CMYK filter, or any other absorption-based or interference-based filters. One type of interference based filter would be an array of thin film filters arranged in a grid with each element of the grid corresponding to one or more sensor elements. Another type of interference based filter is a Fabry-Pérot filter. Nanoetched interference Fabry-Pérot filters, which exhibit typical bandpass full-width-at-half-maxima (FWHM) on the order of 20 to 50 nm, are advantageous because they can be used in some embodiments due to the slow roll-off of the filters' passband seen in the transition from its center wavelength to its blocking band. These filters also exhibit a low OD in these blocking bands further enabling increased sensitivity to light outside of their passbands. These combined effects makes these specific filters sensitive to spectral regions that would otherwise be blocked by the fast roll-off of a high OD interference filter with a similar FWHM made with many thin film layers in a coating deposition process such as in evaporative deposition or in ion-beam sputtering. In embodiments with dye-based CMYK or RGB (Bayer) filter configurations, the slow spectral roll-off and the large FWHM of individual filter passbands are preferred and provide a unique spectral transmission percentage to individual wavelengths throughout an observed spectrum.

Accordingly, the datacube **120** that results from a snapshot imaging system will have one of two properties that can be problematic for precision imaging applications. As a first option, the datacube **120** that results from a snapshot imaging system can have smaller N_x and N_y sizes than the (x, y) size of the detector array and, thus be of lower resolution than the datacube **120**, which would be generated by a scanning imaging system having the same image sensor. As a second option, the datacube **120** that results from a snapshot imaging system can have the same N_x and N_y sizes as the (x, y) size of the detector array due to interpolating values for certain (x, y) positions. However, the interpolation used to generate such a datacube means that certain values in the datacube are not actual measurements of the wavelength of light incident on the sensor, but rather estimates of what the actual measurement may be based on surrounding values.

Another existing option for single-exposure multispectral imaging is the multispectral beamsplitter. In such imaging systems, beamsplitter cubes split incident light into distinct color bands, with each band observed by independent image sensors. While one can change the beamsplitter designs to adjust the measured spectral bands, it is not easy to divide the incident light into more than four beams without compromising the system performance. Thus, four spectral channels appear to be the practical limit of this approach. A closely related method is to use thin-film filters instead of the bulkier beamsplitter cubes/prisms to split the light, however this approach is still limited to about six spectral channels due to space limitations and cumulative transmission losses through successive filters.

The aforementioned problems, among others, are addressed in some embodiments by the disclosed multi-aperture spectral imaging system with curved multi-bandpass filters to filter light incoming through each aperture, and the associated image data processing techniques. This particular configuration is able to achieve all of the design goals of fast imaging speeds, high resolution images, and precise fidelity of detected wavelengths. Accordingly, the disclosed optical design and associated image data processing techniques can be used in portable spectral imaging systems and/or to image moving targets, while still yielding a datacube suitable for high precision applications (e.g., clinical tissue analysis, biometric recognition, transient clinical events). These higher precision applications may include the diagnosis of melanoma in the preceeding stages (0 through 3) before metastasis, the classification of burn wound severity on skin tissue, or the tissue diagnosis of diabetic foot ulcer severity. Accordingly, the small form factor and the snapshot spectral acquisition as depicted in some embodiments will enable the use of this invention in clinical environments with transient events, which include the diagnosis of several different retinopathies (e.g. non proliferative diabetic retinopathy, proliferative diabetic retinopathy, and age-related macular degeneration) and the imaging of moving pediatric patients. Accordingly, it will be appreciated by one of skill in the art that the use of a multi-aperture system with flat or curved multi-bandpass filters, as disclosed herein, represents a significant technological advance over prior spectral imaging implementations. Specifically, the multi-aperture system may enable the collection of 3D spatial images of or relating to object curvature, depth, volume, and/or area based on the calculated disparity of the perspective differences between each aperture. However, the multi-aperture strategies presented here are not limited to any specific filter and may include flat and/or thin filters, based on either interference or absorptive filtering. This invention, as disclosed herein, can be modified to include flat filters in the image space of the imaging system in the event of suitable lenses or apertures that use a small or acceptable range of incidence angles. Filters may also be placed at the aperture stop or at the entrance/exit pupil of the imaging lenses as one skilled in the art of optical engineering may see fit to do so.

Various aspects of the disclosure will now be described with regard to certain examples and embodiments, which are intended to illustrate but not limit the disclosure. Although the examples and embodiments described herein will focus, for the purpose of illustration, on specific calculations and algorithms, one of skill in the art will appreciate the examples are to illustrate only, and are not intended to be limiting. For example, although some examples are presented in the context of a multispectral imaging, the disclosed multi-aperture imaging system and associated filters can be configured to achieve hyperspectral imaging in other implementations. Further, although certain examples are presented as achieving benefits for handheld and/or moving target applications, it will be appreciated that the disclosed imaging system design and associated processing techniques can yield a high precision datacube suitable for fixed imaging systems and/or for analysis of relatively motionless targets.

Overview of Electromagnetic Ranges and Image Sensors

Certain colors or portions of the electromagnetic spectrum are referred to herein, and will now be discussed with respect to their wavelength as defined by the ISO 21348 definitions of irradiance spectral categories. As described further below, in certain imaging applications the wavelength ranges for specific colors can be grouped together to pass through a certain filter.

Electromagnetic radiation ranging from wavelengths of or approximately 760 nm to wavelengths of or approximately 380 nm are typically considered the "visible" spectrum, that is, the portion of the spectrum recognizable by the color receptors of the human eye. Within the visible spectrum, red light typically is considered to have a wavelength of or approximately 700 nanometers (nm), or to be in the range of or approximately 760 nm to 610 nm or approximately 610 nm. Orange light typically is considered to have a wavelength of or approximately 600 nm, or to be in the range of or approximately 610 nm to approximately 591 nm or 591 nm. Yellow light typically is considered to have a wavelength of or approximately 580 nm, or to be in the range of or approximately 591 nm to approximately 570 nm or 570 nm. Green light typically is considered to have a wavelength of or approximately 550 nm, or to be in the range of or approximately 570 nm to approximately 500 nm or 500 nm. Blue light typically is considered to have a wavelength of or approximately 475 nm, or to be in the range of or approximately 500 nm to approximately 450 nm or 450 nm. Violet (purple) light typically is considered to have a wavelength of or approximately 400 nm, or to be in the range of or approximately 450 nm to approximately 360 nm or 360 nm.

Turning to ranges outside of the visible spectrum, infrared (IR) refers to electromagnetic radiation with longer wavelengths than those of visible light, and is generally invisible to the human eye. IR wavelengths extend from the nominal red edge of the visible spectrum at approximately 760 nm or 760 nm to approximately 1 millimeter (mm) or 1 mm. Within this range, near infrared (NIR) refers to the portion of the spectrum that is adjacent to the red range, ranging from wavelengths between approximately 760 nm or 760 nm to approximately 1400 nm or 1400 nm.

Ultraviolet (UV) radiation refers to some electromagnetic radiation with shorter wavelengths than those of visible light, and is generally invisible to the human eye. UV wavelengths extend from the nominal violet edge of the visible spectrum at approximately 40 nm or 40 nm to approximately 400 nm. Within this range, near ultraviolet (NUV) refers to the portion of the spectrum that is adjacent to the violet range, ranging from wavelengths between approximately 400 nm or 400 nm to approximately 300 nm or 300 nm, middle ultraviolet (MUV) ranges from wavelengths between approximately 300 nm or 300 nm to approximately 200 nm or 200 nm, and far ultraviolet (FUV) ranges from wavelengths between approximately 200 nm or 200 nm to approximately 122 nm or 122 nm.

The image sensors described herein can be configured to detect electromagnetic radiation in any of the above-described ranges, depending upon the particular wavelength ranges that are suitable for a particular application. The spectral sensitivity of a typical silicon-based charge-coupled device (CCD) or complementary metal-oxide-semiconductor (CMOS) sensor extends across the visible spectrum, and also extends considerably into the near-infrared (IR) spectrum and sometimes into the UV spectrum. Some implementations can alternatively or additionally use back-illuminated or front-illuminated CCD or CMOS arrays. For applications requiring high SNR and scientific-grade measurements, some implementations can alternatively or additionally use either scientific complementary metal-oxide-semiconductor (sCMOS) cameras or electron multiplying CCD cameras (EMCCD). Other implementations can alternatively or additionally use sensors known to operate in specific color ranges (e.g., short-wave infrared (SWIR), mid-wave infrared (MWIR), or long-wave infrared (LWIR)) and corresponding optical filter arrays, based on the intended applications. These may alternatively or additionally include cameras based around detector materials including indium gallium arsenide (InGaAs) or indium antimonide (InSb) or based around microbolometer arrays.

The image sensors used in the disclosed multispectral imaging techniques may be used in conjunction with an optical filter array such as a color filter array (CFA). Some CFAs can split incoming light in the visible range into red (R), green (G), and blue (B) categories to direct the split visible light to dedicated red, green, or blue photodiode receptors on the image sensor. A common example for a

CFA is the Bayer pattern, which is a specific pattern for arranging RGB color filters on a rectangular grid of photosensors. The Bayer pattern is 50% green, 25% red and 25% blue with rows of repeating red and green color filters alternating with rows of repeating blue and green color filters. Some CFAs (e.g., for RGB-NIR sensors) can also separate out the NIR light and direct the split NIR light to dedicated photodiode receptors on the image sensor.

As such, the wavelength ranges of the filter components of the CFA can determine the wavelength ranges represented by each image channel in a captured image. Accordingly, a red channel of an image may correspond to the red wavelength regions of the color filter and can include some yellow and orange light, ranging from approximately 570 nm or 570 nm to approximately 760 nm or 760 nm in various embodiments. A green channel of an image may correspond to a green wavelength region of a color filter and can include some yellow light, ranging from approximately 570 nm or 570 nm to approximately 480 nm or 480 nm in various embodiments. A blue channel of an image may correspond to a blue wavelength region of a color filter and can include some violet light, ranging from approximately 490 nm or 490 nm to approximately 400 nm or 400 nm in various embodiments. As a person of ordinary skill in the art will appreciate, exact beginning and ending wavelengths (or portions of the electromagnetic spectrum) that define colors of a CFA (for example, red, green, and blue) can vary depending upon the CFA implementation.

Further, typical visible light CFAs are transparent to light outside the visible spectrum. Therefore, in many image sensors the IR sensitivity is limited by a thin-film reflective IR filter at the face of the sensor that blocks the infrared wavelength while passing visible light. However, this may be omitted in some of the disclosed imaging systems to allow of passage of IR light. Thus, the red, green, and/or blue channels may also be used to collect IR wavelength bands. In some implementations the blue channel may also be used to collect certain NUV wavelength bands. The distinct spectral responses of the red, green, and blue channels with regard to their unique transmission efficiencies at each wavelength in a spectral image stack may provide a uniquely weighted response of spectral bands to be unmixed using the known transmission profiles. For example, this may include the known transmission response in IR and UV wavelength regions for the red, blue, and green channels, enabling their use in the collection of bands from these regions.

As described in further detail below, additional color filters can be placed before the CFA along the path of light towards the image sensor in order to selectively refine the specific bands of light that become incident on the image sensor. Some of the disclosed filters can be either a combination of dichroic (thin-film) and/or absorptive filters or a single dichroic and/or absorptive filter. Some of the disclosed color filters can be bandpass filters that pass frequencies within a certain range (in a passband) and reject (attenuates) frequencies outside that range (in a blocking range). Some of the disclosed color filters can be multi-bandpass filters that pass multiple discontinuous ranges of wavelengths. These "wavebands" can have smaller passband ranges, larger blocking range attenuation, and sharper spectral roll-off, which is defined as the steepness of the spectral response as the filter transitions from the passband to the blocking range, than the larger color range of the CFA filter. For example, these disclosed color filters can cover a passband of approximately 20 nm or 20 nm or approximately 40 nm or 40 nm. The particular configuration of such color filters can determine the actual wavelength bands that are incident upon the sensor, which can increase the precision of the disclosed imaging techniques. The color filters described herein can be configured to selectively block or pass specific bands of electromagnetic radiation in any of the above-described ranges, depending upon the particular wavelength bands that are suitable for a particular application.

As described herein, a "pixel" can be used to describe the output generated by an element of the 2D detector array. In comparison, a photodiode, a single photosensitive element in this array, behaves as a transducer capable of converting photons into electrons via the photoelectric effect, which is then in turn converted into a usable signal used to determine the pixel value. A single element of the datacube can be referred to as a "voxel" (e.g., a volume element). A "spectral vector" refers to a vector describing the spectral data at a particular (x, y) position in a datacube (e.g., the spectrum of light received from a particular point in the object space). A single horizontal plane of the datacube (e.g., an image representing a single spectral dimension), is referred to herein as a an "image channel". Certain embodiments described herein may capture spectral video information, and the resulting data dimensions can assume the "hypercube" form $N_xN_yN_\lambda N_t$, where N_t is the number of frames captured during a video sequence.

Overview of Example Multi-Aperture Imaging Systems with Curved Multi-Bandpass Filters

FIG. **3**A depicts a schematic view of an example multi-aperture imaging system **200** with curved multi-bandpass filters, according to the present disclosure. The illustrated view includes a first image sensor region **225**A (photodiodes PD**1**-PD**3**) and a second image sensor region **225**B (photodiodes PD**4**-PD**6**). The photodiodes PD**1**-PD**6** can be, for example, photodiodes formed in a semiconductor substrate, for example in a CMOS image sensor. Generally, each of the photodiodes PD**1**-PD**6** can be a single unit of any material, semiconductor, sensor element or other device that converts incident light into current. It will be appreciated that a small portion of the overall system is illustrated for the purpose of explaining its structure and operation, and that in implementation image sensor regions can have hundreds or thousands of photodiodes (and corresponding color filters). The image sensor regions **225**A and **225**B may be implemented as separate sensors, or as separate regions of the same image sensor, depending upon the implementation. Although FIG. **3**A depicts two apertures and corresponding light paths and sensor regions, it will be appreciated that the optical design principles illustrated by FIG. **3**A can be extended to three or more apertures and corresponding light paths and sensor regions, depending upon the implementation.

The multi-aperture imaging system **200** includes a first opening **210**A that provides a first light path towards the first sensor region **225**A, and a second opening **210**B that provides a first light path towards the second sensor region **225**B. These apertures may be adjustable to increase or decrease the brightness of the light that falls on the image, or so that the duration of particular image exposures can be changed and the brightness of the light that falls on the image sensor regions does not change. These apertures may also be located at any position along the optical axes of this multi-aperture system as deemed reasonable by one skilled in the art of optical design. The optical axis of the optical components positioned along the first light path is illustrated by dashed line **230**A and the optical axis of the optical components positioned along the second light path is illustrated by dashed line **230**B, and it will be appreciated that these dashed lines do not represent a physical structure of the multi-aperture imaging system **200**. The optical axes **230**A, **230**B are separated by a distance D, which can result in disparity between the images captured by the first and second sensor regions **225**A, **225**B. Disparity refers to the distance between two corresponding points in the left and right (or upper and lower) images of a stereoscopic pair, such that the same physical point in the object space can appear in different locations in each image. Processing techniques to compensate for and leverage this disparity are described in further detail below.

Each optical axis **230**A, **230**B passes through a center C of the corresponding aperture, and the optical components can also be centered along these optical axes (e.g., the point of rotational symmetry of an optical component can be positioned along the optical axis). For example, the first curved multi-bandpass filter **205**A and first imaging lens **215**A can be centered along the first optical axis **230**A, and the second curved multi-bandpass filter **205**B and second imaging lens **215**B can be centered along the second optical axis **230**B.

As used herein with respect to positioning of optical elements, "over" and "above" refer to the position of a structure (for example, a color filter or lens) such that light entering the imaging system **200** from the object space propagates through the structure before it reaches (or is incident upon) another structure. To illustrate, along the first light path, the curved multi-bandpass filter **205**A is positioned above the aperture **210**A, the aperture **210**A is positioned above imaging lens **215**A, the imaging lens **215**A is positioned above the CFA **220**A, and the CFA **220**A is positioned above the first image sensor region **225**A. Accordingly, light from the object space (e.g., the physical space being imaged) first passes through the curved multi-bandpass filter **205**A, then the aperture **210**A, then the imaging lens **215**A, then the CFA **220**A, and finally is incident on the first image sensor region **225**A. The second light path (e.g., curved multi-bandpass filter **205**B, aperture **210**B, imaging lens **215**B, CFA **220**B, second image sensor region **225**B) follows a similar arrangement. In other implementations, the aperture **210**A, **210**B and/or imaging lenses **215**A, **215**B can be positioned above the curved multi-bandpass filter **205**A, **205**B. Additionally, other implementations may not use a physical aperture and may rely on the clear aperture of the optics to control the brightness of light that is imaged onto the sensor region **225**A, **225**B. Accordingly, the lens **215**A, **215**B may be placed above the aperture **210**A, **210**B and curved multi-bandpass filter **205**A, **205**B. In this implementation, the aperture **210**A, **210**B and lens **215**A, **215**B may be also be placed over or under each other as deemed necessary by one skilled in the art of optical design.

The first CFA **220**A positioned over the first sensor region **225**A and the second CFA **220**B positioned over the second sensor region **225**B can act as wavelength-selective pass filters and split incoming light in the visible range into red, green, and blue ranges (as indicated by the R, G, and B notation). The light is "split" by allowing only certain selected wavelengths to pass through each of the color filters in the first and second CFAs **220**A, **220**B. The split light is received by dedicated red, green, or blue diodes on the image sensor. Although red, blue, and green color filters are commonly used, in other embodiments the color filters can vary according to the color channel requirements of the captured image data, for example including ultraviolet, infrared, or near-infrared pass filters, as with an RGB-IR CFA.

As illustrated, each filter of the CFA is positioned over a single photodiode PD**1**-PD**6**. FIG. **3**A also illustrates example microlenses (denoted by ML) that can be formed on or otherwise positioned over each color filter, in order to focus incoming light onto active detector regions. Other implementations may have multiple photodiodes under a single filter (e.g., clusters of 2, 4, or more adjacent photodiodes). In the illustrated example, photodiode PD**1** and photodiode PD**4** are under red color filters and thus would output red channel pixel information; photodiode PD**2** and photodiode PD**5** are under green color filters and, thus would output green channel pixel information; and photodiode PD**3** and photodiode PD**6** are under blue color filters and thus would output blue channel pixel information. Further, as described in more detail below, the specific color channels output by given photodiodes can be further limited to narrower wavebands based on activated illuminants and/or the specific wavebands passed by the multi-bandpass filters **205**A, **205**B, such that a given photodiode can output different image channel information during different exposures.

The imaging lenses **215**A, **215**B can be shaped to focus an image of the object scene onto the sensor regions **225**A, **225**B. Each imaging lens **215**A, **215**B may be composed of as many optical elements and surfaces needed for image formation and are not limited to single convex lenses as presented in FIG. **3**A, enabling the use of a wide variety of imaging lenses or lens assemblies that would be available commercially or by custom design. Each element or lens assembly may be formed or bonded together in a stack or held in series using an optomechanical barrel with a retaining ring or bezel. In some embodiments, elements or lens assemblies may include one or more bonded lens groups, such as two or more optical components cemented or otherwise bonded together. In various embodiments, any of the multi-bandpass filters described herein may be positioned in front of a lens assembly of the multispectral image system, in front of a singlet of the multispectral image system, behind a lens assembly of the multispectral image system, behind a singlet of the multispectral image system, inside a lens assembly of the multispectral image system, inside a bonded lens group of the multispectral image system, directly onto a surface of a singlet of the multispectral image system, or directly onto a surface of an element of a lens assembly of the multispectral image system. Further, the aperture **210**A and **210**B may be removed, and the lenses **215**A, **215**B may be of the variety typically used in photography with either digital-single-lens-reflex (DSLR) or mirrorless cameras. Additionally, these lenses may be of the variety used in machine vision using C-mount or S-mount threading for mounting. Focus adjustment can be provided by movement of the imaging lenses **215**A, **215**B relative to the sensor regions **225**A, **225**B or movement of the sensor regions **225**A, **225**B relative to the imaging lenses **215**A, **215**B, for example based on manual focusing, contrast-based autofocus, or other suitable autofocus techniques.

The multi-bandpass filters **205**A, **205**B can be each configured to selectively pass multiple narrow wavebands of light, for example wavebands of 10-50 nm in some embodiments (or wider or narrower wavebands in other embodiments). As illustrated in FIG. **3**A, both multi-bandpass filters **205**A, **205**B can pass waveband λ_c (the "common waveband"). In implementations with three or more light paths, each multi-bandpass filter can pass this common waveband. In this manner, each sensor region captures image information at the same waveband (the "common channel"). This image information in this common channel can be used to register the sets of images captured by each sensor region, as described in further detail below. Some implementations may have one common waveband and corresponding common channel, or may have multiple common wavebands and corresponding common channels.

In addition to the common waveband λ_c, each multi-bandpass filters **205**A, **205**B can be each configured to selectively pass one or more unique wavebands. In this manner, the imaging system **200** is able to increase the number of distinct spectral channels captured collectively by the sensor regions **205**A, **205**B beyond what can be captured by a single sensor region. This is illustrated in FIG. **3**A by multi-bandpass filters **205**A passing unique waveband λ_{u1}, and multi-bandpass filters **205**B passing unique waveband λ_{u2}, where λ_{u1} and λ_{u2} represent different wavebands from one another. Although depicted as passing two wavebands, the disclosed multi-bandpass can each pass a set of two or more wavebands. For example, some implementations can pass four wavebands each, as described with respect to FIGS. **11**A and **11**B. In various embodiments, a larger number of wavebands may be passed. For example, some four-camera implementations may include multi-bandpass filters configured to pass 8 wavebands. In some embodiments, the number of wavebands may be, for example, 4, 5, 6, 7, 8, 9, 10, 12, 15, 16, or more wavebands.

The multi-bandpass filters **205**A, **205**B have a curvature selected to reduce the angular-dependent spectral transmission across the respective sensor regions **225**A, **225**B. As a result, when receiving narrowband illumination from the object space, each photodiode across the area of the sensor regions **225**A, **225**B that is sensitive to that wavelength (e.g., the overlying color filter passes that wavelength) should receive substantially the same wavelength of light, rather than photodiodes near the edge of the sensor experiencing the wavelength shift described above with respect to FIG. **1**A. This can generate more precise spectral image data than using flat filters.

FIG. **3**B depicts an example optical design for optical components of one light path of the multi-aperture imaging system of FIG. **3**A. Specifically, FIG. **3**B depicts a custom achromatic doublet **240** that can be used to provide the multi-bandpass filters **205**A, **205**B. The custom achromatic doublet **240** passes light through a housing **250** to an image sensor **225**. The housing **250** can include openings **210**A, **210**B and imaging lens **215**A, **215**B described above.

The achromatic doublet **240** is configured to correct for optical aberrations as introduced by the incorporation of surfaces required for the multi-bandpass filter coatings **205**A, **205**B. The illustrated achromatic doublet **240** includes two individual lenses, which can be made from glasses or other optical materials having different amounts of dispersion and different refractive indices. Other implementations may use three or more lenses. These achromatic doublet lenses can be designed to incorporate the multi-bandpass filter coatings **205**A, **205**B on the curved front surface **242** while eliminating optical aberrations introduced that would otherwise be present through the incorporation of a curved singlet optical surface with the deposited filter coatings **205**A, **205**B while still limiting optical or focusing power provided by the achromatic doublet **240** due to the combinatorial effect of the curved front surface **242** and the curved back surface of **244** while still keeping the primary elements for focusing light restricted to the lenses housed in housing **250**. Thus, the achromatic doublet **240** can contribute to the high precision of image data captured by the system **200**. These individual lenses can be mounted next to each other, for example being bonded or cemented together, and shaped such that the aberration of one of the lenses is counterbalanced by that of the other. The achromatic doublet **240** curved front surface **242** or the curved back surface **244** can be coated with the multi-bandpass filter coating **205**A, **205**B. Other doublet designs may be implemented with the systems described herein.

Further variations of the optical designs described herein may be implemented. For example, in some embodiments a light path may include a singlet or other optical singlet such as of the positive or negative meniscus variety as depicted in FIG. **3**A instead of the doublet **240** depicted in FIG. **3**B. FIG. **3**C illustrates an example implementation in which a flat filter **252** is included between the lens housing **250** and the sensor **225**. The achromatic doublet **240** in FIG. **3**C provides optical aberration correction as introduced by the inclusion of the flat filter **252** containing a multi-bandpass transmission profile while not significantly contributing to the optical power as provided by the lenses contained in housing **250**. FIG. **3**D illustrates another example of an implementation in which the multi-bandpass coating is implemented by means of a multi-bandpass coating **254** applied to the front surface of the lens assembly contained within the housing **250**. As such, this multi-bandpass coating **254** may be applied to any curved surface of any optical element residing within housing **250**.

FIGS. **4**A-**4**E depict an embodiment of a multi spectral, multi-aperture imaging system **300**, with an optical design as described with respect to FIGS. **3**A and **3**B. Specifically, FIG. **4**A depicts a perspective view of the imaging system **300** with the housing **305** illustrated with translucency to reveal interior components. The housing **305** may be larger or smaller relative to the illustrated housing **305**, for example, based on a desired amount of embedded computing resources. FIG. **4**B depicts a front view of the imaging system **300**. FIG. **4**C depicts a cutaway side view of the imaging system **300**, cut along line C-C illustrated in FIG. **4**B. FIG. **4**D depicts a bottom view of the imaging system **300** depicting the processing board **335**. FIGS. **4**A-**4**D are described together below.

The housing **305** of the imaging system **300** may be encased in another housing. For example, handheld implementations may enclose the system within a housing optionally with one or more handles shaped to facilitate stable holding of the imaging system **300**. Example handheld implementations are depicted in greater detail in FIGS. **18**A-**18**C and in FIGS. **19**A-**19**B. The upper surface of the housing **305** includes four openings **320**A-**320**D. A different multi-bandpass filter **325**A-**325**D is positioned over each opening **320**A-**320**D and held in place by a filter cap **330**A-**330**B. The multi-bandpass filters **325**A-**325**D may be curved, and each pass a common waveband and at least one unique waveband, as described herein, in order to achieve high precision multi-spectral imaging across a greater number of spectral channels than would otherwise be captured by the image sensor due to its overlying color filter array. The image sensor, imaging lenses, and color filters described above are positioned within the camera housings **345**A-**345**D. In some embodiments, a single camera housing may enclose the image sensors, imaging lenses, and color filters described above, for example, as shown in FIGS. **20**A-**20**B. In the depicted implementation separate sensors are thus used (e.g., one sensor within each camera housing **345**A-**345**D), but it will be appreciated that a single image sensor spanning across all of the regions exposed through the openings **320**A-**320**D could be used in other implementations. The camera housings **345**A-**345**D are secured to the system housing **305** using supports **340** in this embodiment, and can be secured using other suitable means in various implementations.

The upper surface of the housing **305** supports an optional illumination board **310** covered by an optical diffusing element **315**. The illumination board **310** is described in further detail with respect to FIG. **4**E, below. The diffusing element **315** can be composed of glass, plastic, or other optical material for diffusing light emitted from the illumination board **310** such that the object space receives substantially spatially-even illumination. Even illumination of the target object can be beneficial in certain imaging applications, for example clinical analysis of imaged tissue, because it provides, within each wavelength, a substantially even amount of illumination across the object surface. In some embodiments, the imaging systems disclosed herein may utilize ambient light instead of or in addition to light from the optional illumination board.

Due to heat generated by the illumination board **310** in use, the imaging system **300** includes a heat sink **350** including a number of heat dissipating fins **355**. The heat dissipating fins **355** can extend into the space between the camera housings **345**A-**345**D, and the upper portion of the heat sink **350** can draw heat from the illumination board **310** to the fins **355**. The heat sink **350** can be made from suitable thermally conductive materials. The heat sink **350** may further help to dissipate heat from other components such that some implementations of imaging systems may be fanless.

A number of supports **365** in the housing **305** secure a processing board **335** in communication with the cameras **345**A-**345**D. The processing board **335** can control operation of the imaging system **300**. Although not illustrated, the imaging system **300** can also be configured with one or more memories, for example storing data generated by use of the imaging system and/or modules of computer-executable instructions for system control. The processing board **335** can be configured in a variety of ways, depending upon system design goals. For example, the processing board can be configured (e.g., by a module of computer-executable instructions) to control activation of particular LEDs of the illumination board **310**. Some implementations can use a highly stable synchronous step-down LED driver, which can enable software control of analog LED current and also detect LED failure. Some implementations can additionally provide image data analysis functionality to the processing board (e.g., by modules of computer-executable instructions) **335** or to a separate processing board. Although not illustrated, the imaging system **300** can include data interconnects between the sensors and the processing board **335** such that the processing board **335** can receive and process data from the sensors, and between the illumination board **310** and the processing board **335** such that the processing board can drive activation of particular LEDs of the illumination board **310**.

FIG. **4**E depicts an example illumination board **310** that may be included in the imaging system **300**, in isolation from the other components. The illumination board **310** includes four arms extending from a central region, with LEDs positioned along each arm in three columns. The spaces between LEDs in adjacent columns are laterally offset from one another to create separation between adjacent LEDs. Each column of LEDs includes a number of rows having different colors of LEDs. Four green LEDs **371** are positioned in the center region, with one green LED in each corner of the center region. Starting from the innermost row (e.g., closest to the center), each column includes a row of two deep red LEDs **372** (for a total of eight deep red LEDs). Continuing radially outward, each arm has a row of one amber LED **374** in the central column, a row of two short blue LEDs **376** in the outermost columns (for a total of eight short blue LEDs), another row of one amber LED **374** in the central column (for a total of eight amber LEDs), a row having one non-PPG NIR LED **373** and one red LED **375** in the outermost columns (for a total of four of each), and one PPG NIR LED **377** in the central column (for a total of four PPG NIR LEDs). A "PPG" LED refers to an LED activated during a number of sequential exposure for capturing photoplethysmographic (PPG) information representing pulsatile blood flow in living tissue. It will be understood that a variety of other colors and/or arrangements thereof may be used in illumination boards of other embodiments.

FIG. **5** depicts another embodiment of a multispectral multi-aperture imaging system, with an optical design as described with respect to FIGS. **3**A and **3**B. Similar to the design of the imaging system **300**, the imaging system **400** includes four light paths, here shown as openings **420**A-**420**D having multi-bandpass filter lens groups **425**A-**425**D, which are secured to housing **405** by retaining rings **430**A-**430**D. The imaging system **400** also includes an illumination board **410** secured to the front face of the housing **405** between the retaining rings **430**A-**430**D, and a diffuser **415** positioned over the illumination board **410** to assist with emitting spatially even light onto the target object.

The illumination board **410** of the system **400** includes four branches of LEDs in a cross shape, with each branch including two columns of closely-spaced LEDs. Thus, the illumination board **410** is more compact than the illumination board **310** described above, and may be suitable for use with imaging systems having smaller form factor requirements. In this example configuration, each branch includes an outermost row having one green LED and one blue LED, and moving inwards includes two rows of yellow LEDs, a row of orange LEDs, a row having one red LED and one deep red LED, and a row having one amber LED and one NIR LED. Accordingly, in this implementation the LEDs are arranged such that LEDs that emit light of longer wavelengths are in the center of the illumination board **410**, while LEDs that emit light of shorter wavelengths are at the edges of the illumination board **410**.

FIGS. **6**A-**6**C depict another embodiment of a multispectral multi-aperture imaging system **500**, with an optical design as described with respect to FIGS. **3**A and **3**B. Specifically, FIG. **6**A depicts a perspective view of the imaging system **500**, FIG. **6**B depicts a front view of the imaging system **500**, and FIG. **6**C depicts a cutaway side view of the imaging system **500**, cut along line C-C illustrated in FIG. **6**B. The imaging system **500** includes similar components to those described above with respect to imaging system **300** (e.g., a housing **505**, illumination board **510**, diffusing plate **515**, multi-bandpass filters **525**A-**525**D secured over openings via retaining rings **530**A-**530**D), but depicts a shorter form factor (e.g., in an embodiment with fewer and/or smaller embedded computing components). The system **500** also includes a direct camera-to-frame mount **540** for added rigidity and robustness of camera alignment.

FIGS. **7**A-**7**B depict another embodiment of a multispectral multi-aperture imaging system **600**. FIGS. **7**A-**7**B illustrate another possible arrangement of light sources **610**A-**610**C around a multi-aperture imaging system **600**. As depicted, four lens assemblies with multi-bandpass filters **625**A-**625**D with an optical design as described with respect to FIGS. **3**A-**3**D can be disposed in a rectangular or square configuration to provide light to four cameras **630**A-**630**D (including image sensors). Three rectangular light emitting elements **610**A-**610**C can be disposed parallel to one another outside of and between the lens assemblies with multi-bandpass filters **625**A-**625**D. These can be broad-spectrum light emitting panels or arrangements of LEDs that emit discrete wavebands of light.

FIGS. **8**A-**8**B depict another embodiment of a multispectral multi-aperture imaging system **700**. FIGS. **8**A-**8**B illustrate another possible arrangement of light sources **710**A-**710**D around a multi-aperture imaging system **700**. As depicted, four lens assemblies with multi-bandpass filters **725**A-**725**D, employing an optical design as described with respect to FIGS. **3**A-**3**D, can be disposed in a rectangular or square configuration to provide light to four cameras **730**A-**730**D (including image sensors). The four cameras **730**A-**730**D are illustrated in a closer example configuration which may minimize perspective differences between the lenses. Four rectangular light emitting elements **710**A-**710**D can be positioned in a square surrounding the lens assemblies with multi-bandpass filters **725**A-**725**D. These can be broad-spectrum light emitting panels or arrangements of LEDs that emit discrete wavebands of light.

FIGS. **9**A-**9**C depict another embodiment of a multispectral multi-aperture imaging system **800**. The imaging system **800** includes a frame **805** coupled to a lens cluster frame front **830** that includes openings **820** and support structures for micro-video lenses **825**, which can be provided with multi-bandpass filters using an optical design as described with respect to FIGS. **3**A-**3**D. The micro-video lenses **825** provide light to four cameras **845** (including imaging lenses and image sensor regions) mounted on a lens cluster frame back **840**. Four linear arrangements of LEDs **811** are disposed along the four sides of the lens cluster frame front **830**, each provided with its own diffusing element **815**. FIGS. **9**B and **9**C depict example dimensions in inches to show one possible size of the multi-aperture imaging system **800**.

FIG. **10**A depicts another embodiment of a multispectral multi-aperture imaging system **900**, with an optical design as described with respect to FIGS. **3**A-**3**D. The imaging system **900** can be implemented as a set of multi-bandpass filters **905** that are attachable over a multi-aperture camera **915** of a mobile device **910**. For example, certain mobile devices **910** such as smartphones can be equipped with stereoscopic imaging systems having two openings leading to two image sensor regions. The disclosed multi-aperture spectral imaging techniques can be implemented in such devices by providing them with a suitable set of multi-bandpass filters **905** to pass multiple narrower wavebands of light to the sensor regions. Optionally, the set of multi-bandpass filters **905** can be equipped with an illuminant (such as an LED array and diffuser) that provides light at these wavebands to the object space.

The system **900** can also include a mobile application that configures the mobile device to perform the processing that generates the multispectral datacube, as well as processing the multi spectral datacube (e.g., for clinical tissue classification, biometric recognition, materials analysis, or other applications). Alternatively, the mobile application may configure the device **910** to send the multispectral datacube over a network to a remote processing system, and then receive and display a result of the analysis. An example user interface **910** for such an application is shown in FIG. **10**B.

FIGS. **11**A-**11**B depict an example set of wavebands that can be passed by the filters of four-filter implementations of the multispectral multi-aperture imaging systems of FIGS. **3**A-**10**B, for example to an image sensor having the Bayer CFA (or another RGB or RGB-IR CFA). The spectral transmission response of wavebands as passed by the multi-bandpass filters are shown by the solid lines in the graphs **1000** of FIG. **11**A and are denoted by T_n^{λ}, where n represents the camera number, ranging from 1 through 4. The dashed lines represent the combined spectral response of T_n^{λ} with either the spectral transmission of a green pixel, Q_G^{λ}, a red pixel, Q_R^{λ}, or a blue pixel, Q_B^{λ}, that would be present in a typical Bayer CFA. These transmission curves also include the effects of quantum efficiency due to the sensor used in this example. As illustrated, this set of four cameras collectively captures eight unique channels or wavebands. Each filter passes two common wavebands (the two left-most peaks) to the respective cameras, as well as two additional wavebands. In this implementation, the first and third cameras receive light in a first shared NIR waveband (the right-most peak), and the second and fourth cameras receive light in a second shared NIR waveband (the peak second-most to the right). Each of the cameras also receives one unique waveband ranging from approximately 550 nm or 550 nm to approximately 800 nm or 800 nm. Thus, the camera can capture eight unique spectral channels using a compact configuration. A graph **1010** in FIG. **11**B depicts the spectral irradiance of an LED board as described in FIG. **4**E that may be used as illumination for the 4 cameras d shown in FIG. **11**A.

In this implementation, the eight wavebands have been selected based on producing spectral channels suitable for clinical tissue classification, and may also be optimized with respect to signal-to-noise ratio (SNR) and frame rate while limiting the number of LEDs (which introduce heat into the imaging system). The eight wavebands include a common waveband of blue light (the leftmost peak in the graphs **1000**) that is passed by all four filters, because tissue (e.g., animal tissue including human tissue) exhibits higher contrast at blue wavelengths than at green or red wavelengths. Specifically, human tissue exhibits its highest contrast when imaged at a waveband centered on around 420 nm, as shown in the graphs **1000**. Because the channel corresponding to the common waveband is used for disparity correction, this higher contrast can produce more accurate correction. For example in disparity correction the image processor can employ local or global methods to find a set of disparities so that a figure of merit corresponding to similarity between local image patches or images is maximized. Alternatively, the image processor can employ similar methods that minimize a figure of merit corresponding to dissimilarity. These figures of merit can be based on entropy, correlation, absolute differences, or on deep learning methods. Global methods of disparity calculation can operate iteratively, terminating when the figure of merit is stable. Local methods can be used to calculate disparity point by point, using a fixed patch in one image as an input into the figure of merit and a number of different patches, each determined by a different value of disparity under test, from the other image. All such methods can have constraints imposed on the range of disparities that are considered. These constraints can be based on knowledge of the object depth and distance, for instance. The constraints could also be imposed based on a range of gradients expected in an object. Constraints on the calculated disparities can also be imposed by projective geometry, such as the epipolar constraint. Disparity can be calculated at multiple resolutions, with the output of disparities calculated at lower resolutions acting as initial values or constraints on the disparities calculated at the next level of resolution. For instance, a disparity calculated at a resolution level of 4 pixels in one calculation can be used to set constraints of ±4 pixels in a next calculation of disparity at higher resolution. All algorithms that calculate from disparity will benefit from higher contrast, particularly if that source of contrast is correlated for all viewpoints. Generally speaking, the common waveband can be selected based on corresponding to the highest contrast imaging of the material that is expected to be imaged for a particular application.

After image capture, color separation between adjacent channels may not be perfect, and so this implementation also has an additional common waveband passed by all filters—depicted in the graphs **1000** as the green waveband adjacent to the blue waveband. This is because blue color filter pixels are sensitive to retions of the green spectrum due to its broad spectral bandpass. This typically manifests as spectral overlap, which may also be characterized as intentional cross-talk, between adjacent RGB pixels. This overlap enables the spectral sensitivity of color cameras to be similar to the spectral sensitivity of a human retina, such that the resultant color space is qualitatively similar to human vision. Accordingly, having a common green channel can enable separation of the portion of the signal generated by blue photodiodes that truly corresponds to received blue light, by separating out the portion of the signal due to green light. This can be accomplished using spectral unmixing algorithms that factor in the transmittance (shown in the legend by T with a solid black line) of the multi-band pass filter, the transmittance of the corresponding CFA color filter (shown in the legend by Q with dashed red, green, and blue lines). It will be appreciated that some implementations may use red light as a common waveband, and in such instances a second common channel may not be necessary.

FIG. **12** illustrates a high-level block diagram of an example compact imaging system **1100** with high resolution spectral imaging capabilities, the system **1100** having a set of components including a processor **1120** linked to an multi-aperture spectral camera **1160** and illuminant(s) **1165**. A working memory **1105**, storage **1110**, electronic display **1125**, and memory **1130** are also in communication with the processor **1120**. As described herein, the system **1100** may capture a greater number of image channels than there are different colors of filters in the CFA of the image sensor by using different multi-bandpass filters placed over different openings of the multi-aperture spectral camera **1160**.

System **1100** may be a device such as cell phone, digital camera, tablet computer, personal digital assistant, or the like. System **1100** may also be a more stationary device such as a desktop personal computer, video conferencing station, or the like that uses an internal or external camera for capturing images. System **1100** can also be a combination of an image capture device and a separate processing device receiving image data from the image capture device. A plurality of applications may be available to the user on system **1100**. These applications may include traditional photographic applications, capture of still images and video, dynamic color correction applications, and brightness shading correction applications, among others.

The image capture system **1100** includes the multi-aperture spectral camera **1160** for capturing images. The multi-aperture spectral camera **1160** can be, for example, any of the devices of FIGS. **3A-10B**. The multi-aperture spectral camera **1160** may be coupled to the processor **1120** to transmit captured images in different spectral channels and from different sensor regions to the image processor **1120**. The illuminant(s) **1165** can also be controlled by the processor to emit light at certain wavelengths during certain exposures, as described in more detail below. The image processor **1120** may be configured to perform various operations on a received captured image in order to output a high quality, disparity corrected multispectral datacube.

Processor **1120** may be a general purpose processing unit or a processor specially designed for imaging applications. As shown, the processor **1120** is connected to a memory **1130** and a working memory **1105**. In the illustrated embodiment, the memory **1130** stores a capture control module **1135**, datacube generation module **1140**, datacube analysis module **1145**, and operating system **1150**. These modules include instructions that configure the processor to perform various image processing and device management tasks. Working memory **1105** may be used by processor **1120** to store a working set of processor instructions contained in the modules of memory **1130**. Alternatively, working memory **1105** may also be used by processor **1120** to store dynamic data created during the operation of device **1100**.

As mentioned above, the processor **1120** is configured by several modules stored in the memory **1130**. The capture control module **1135** includes instructions that configure the processor **1120** to adjust the focus position of the multi-aperture spectral camera **1160**, in some implementations. The capture control module **1135** also includes instructions that configure the processor **1120** to capture images with the multi-aperture spectral camera **1160**, for example multispectral images captured at different spectral channels as well as PPG images captured at the same spectral channel (e.g., a NIR channel). Non-contact PPG imaging normally uses near-infrared (NIR) wavelengths as illumination to take advantage of the increased photon penetration into the tissue at this wavelength. Therefore, processor **1120**, along with capture control module **1135**, multi-aperture spectral camera **1160**, and working memory **1105** represent one means for capturing a set of spectral images and/or a sequence of images.

The datacube generation module **1140** includes instructions that configure the processor **1120** to generate a multispectral datacube based on intensity signals received from the photodiodes of different sensor regions. For example, the datacube generation module **1140** can estimate a disparity between the same regions of an imaged object based on a spectral channel corresponding to the common waveband passed by all multi-bandpass filters, and can use this disparity to register all spectral images across all captured channels to one another (e.g., such that the same point on the object is represented by substantially the same (x,y) pixel location across all spectral channels). The registered images collectively form the multispectral datacube, and the disparity information may be used to determine depths of different imaged objects, for example a depth difference between healthy tissue and a deepest location within a wound site. In some embodiments, the datacube generation module **1140** may also perform spectral unmixing to identify which portions of the photodiode intensity signals correspond to which passed wavebands, for example based on spectral unmixing algorithms that factor in filter transmittances and sensor quantum efficiency.

The datacube analysis module **1145** can implement various techniques to analyze the multispectral datacube generated by the datacube generation module **1140**, depending upon the application. For example, some implementations of the datacube analysis module **1145** can provide the multispectral datacube (and optionally depth information) to a machine learning model trained to classify each pixel according to a certain state. These states may be clinical states in the case of tissue imaging, for example burn states (e.g., first degree burn, second degree burn, third degree burn, or healthy tissue categories), wound states (e.g., hemostasis, inflammation, proliferation, remodeling or healthy skin categories), healing potential (e.g., a score reflecting the likelihood that the tissue will heal from a wounded state, with or without a particular therapy), perfusion states, cancerous states, or other wound-related tissue states. The datacube analysis module **1145** can also analyze the multispectral datacube for biometric recognition and/or materials analysis.

Operating system module **1150** configures the processor **1120** to manage the memory and processing resources of the system **1100**. For example, operating system module **1150** may include device drivers to manage hardware resources such as the electronic display **1125**, storage **1110**, multi-aperture spectral camera **1160**, or illuminant(s) **1165**. Therefore, in some embodiments, instructions contained in the image processing modules discussed above may not interact with these hardware resources directly, but instead interact through standard subroutines or APIs located in operating system component **1150**. Instructions within operating system **1150** may then interact directly with these hardware components.

The processor **1120** may be further configured to control the display **1125** to display the captured images and/or a result of analyzing the multispectral datacube (e.g., a classified image) to a user. The display **1125** may be external to an imaging device including the multi-aperture spectral camera **1160** or may be part of the imaging device. The display **1125** may also be configured to provide a view finder for a user prior to capturing an image. The display **1125** may comprise an LCD or LED screen, and may implement touch sensitive technologies.

Processor **1120** may write data to storage module **1110**, for example data representing captured images, multispectral datacubes, and datacube analysis results. While storage module **1110** is represented graphically as a traditional disk device, those with skill in the art would understand that the storage module **1110** may be configured as any storage media device. For example, the storage module **1110** may include a disk drive, such as a floppy disk drive, hard disk drive, optical disk drive or magneto-optical disk drive, or a solid state memory such as a FLASH memory, RAM, ROM, and/or EEPROM. The storage module **1110** can also include multiple memory units, and any one of the memory units may be configured to be within the image capture device **1100**, or may be external to the image capture system **1100**. For example, the storage module **1110** may include a ROM memory containing system program instructions stored within the image capture system **1100**. The storage module **1110** may also include memory cards or high speed memories configured to store captured images which may be removable from the camera.

Although FIG. **12** depicts a system comprising separate components to include a processor, imaging sensor, and memory, one skilled in the art would recognize that these separate components may be combined in a variety of ways to achieve particular design objectives. For example, in an alternative embodiment, the memory components may be combined with processor components to save cost and improve performance.

Additionally, although FIG. **12** illustrates two memory components—memory component **1130** comprising several modules and a separate memory **1105** comprising a working memory-one with skill in the art would recognize several embodiments utilizing different memory architectures. For example, a design may utilize ROM or static RAM memory for the storage of processor instructions implementing the modules contained in memory **1130**. Alternatively, processor instructions may be read at system startup from a disk storage device that is integrated into system **1100** or connected via an external device port. The processor instructions may then be loaded into RAM to facilitate execution by the processor. For example, working memory **1105** may be a RAM memory, with instructions loaded into working memory **1105** before execution by the processor **1120**.

Overview of Example Image Processing Techniques

FIG. **13** is a flowchart of an example process **1200** for capturing image data using the multispectral multi-aperture imaging systems of FIGS. **3A-10B** and **12**. FIG. **13** depicts four example exposures that can be used to generate a multispectral datacube as described herein—a visible exposure **1205**, an additional visible exposure **1210**, a non-visible exposure **1215**, and an ambient exposure **1220**. It will be appreciated that these may be captured in any order, and some exposures may be optionally removed from or added to a particular workflow as described below. Further, the process **1200** is described with reference to the wavebands of FIGS. **11A** and **11B**, however similar workflows can be implemented using image data generated based on other sets of wavebands. Additionally, flat field correction may further be implemented in accordance with various known flat field correction techniques, to improve image acquisition and/or disparity correction in various embodiments.

For the visible exposure **1205**, LEDs of first five peaks (the left five peaks corresponding to visible light in the graphs **1000** of FIG. **11A**) can be turned on by a control signal to the illumination board. The wave of light output may need to stabilize, at a time specific to particular LEDs, for example 10 ms. The capture control module **1135** can begin the exposure of the four cameras after this time and can continue this exposure for a duration of around 30 ms, for example. Thereafter, the capture control module **1135** can cease the exposure and pull the data off of the sensor regions (e.g., by transferring raw photodiode intensity signals to the working memory **1105** and/or data store **1110**). This data can include a common spectral channel for use in disparity correction as described herein.

In order to increase the SNR, some implementations can capture the additional visible exposure **1210** using the same process described for the visible exposure **1205**. Having two identical or near-identical exposures can increase the SNR to yield more accurate analysis of the image data. However, this may be omitted in implementations where the SNR of a single image is acceptable. A duplicate exposure with the common spectral channel may also enable more accurate disparity correction in some implementations.

Some implementations can also capture a non-visible exposure **1215** corresponding to NIR or IR light. For example, the capture control module **1135** can activate two different NIR LEDs corresponding to the two NIR channels shown in FIG. **11A**. The wave of light output may need to stabilize, at a time specific to particular LEDs, for example 10 ms. The capture control module **1135** can begin the exposure of the four cameras after this time and continue this exposure for a duration of around 30 ms, for example. Thereafter, the capture control module **1135** can cease the exposure and pull the data off of the sensor regions (e.g., by transferring raw photodiode intensity signals to the working memory **1105** and/or data store **1110**). In this exposure, there may be no common waveband passed to all sensor regions, as it can safely be assumed that there is no change in the shape or positioning of the object relative to the exposures **1205**, **1210** and, thus previously computed disparity values can be used to register the NIR channels.

In some implementations, multiple exposures can be captured sequentially to generate PPG data representing the change in shape of a tissue site due to pulsatile blood flow. These PPG exposures may be captured at a non-visible wavelength in some implementations. Although the combination of PPG data with multi spectral data may increase the accuracy of certain medical imaging analyses, the capture of PPG data can also introduce additional time into the image capture process. This additional time can introduce errors due to movement of the handheld imager and/or object, in some implementations. Thus, certain implementations may omit capture of PPG data.

Some implementations can additionally capture the ambient exposure **1220**. For this exposure, all LEDs can be turned off to capture an image using ambient illumination (e.g., sunlight, light from other illuminant sources). The capture control module **1135** can begin the exposure of the four cameras after this time and can keep the exposure ongoing for a desired duration of, for example, around 30 ms. Thereafter, the capture control module **1135** can cease the exposure and pull the data off of the sensor regions (e.g., by transferring raw photodiode intensity signals to the working memory **1105** and/or data store **1110**). The intensity values of the ambient exposure **1220** can be subtracted from the values of the visible exposure **1205** (or the visible exposure **1205** corrected for SNR by the second exposure **1210**) and also from the non-visible exposure **1215** in order to remove the influence of ambient light from the multispectral datacube. This can increase the accuracy of downstream analysis by isolating the portion of the generated signals that represent light emitted by the illuminants and reflected from the object/tissue site. Some implementations may omit this step if analytical accuracy is sufficient using just the visible **1205**, **1210** and non-visible **1215** exposures.

It will be appreciated that the particular exposure times listed above are examples of one implementation, and that in other implementations exposure time can vary depending upon the image sensor, illuminant intensity, and imaged object.

FIG. **14** depicts a schematic block diagram of a workflow **1300** for processing image data, for example image data captured using the process **1200** of FIG. **13** and/or using the multi spectral multi-aperture imaging systems of FIGS. **3**A-**10**B and **12**. The workflow **1300** shows the output of two RGB sensor regions **1301**A, **1301**B, however the workflow **1300** can be extended to greater numbers of sensor regions and sensor regions corresponding to different CFA color channels.

The RGB sensor outputs from the two sensor regions **1301**A, **1301**B are stored at the 2D sensor outputs modules **1305**A, **1305**B, respectively. The values of both sensor regions are sent to the non-linear mapping modules **1310**A, **1310**B, which can perform disparity correction by identifying disparity between the captured images using the common channel and then applying this determined disparity across all channels to register all spectral images to one another.

The outputs of both non-linear mapping modules **1310**A, **1310**B are then provided to the depth calculation module **1335**, which can compute a depth of a particular region of interest in the image data. For example, the depth may represent the distance between the object and the image sensor. In some implementations, multiple depth values can be computed and compared to determine the depth of the object relative to something other than the image sensor. For example, a greatest depth of a wound bed can be determined, as well as a depth (greatest, lowest, or average) of healthy tissue surrounding the wound bed. By subtracting the depth of the healthy tissue from the depth of the wound bed, the deepest depth of the wound can be determined. This depth comparison can additionally be performed at other points in the wound bed (e.g., all or some predetermined sampling) in order to build a 3D map of the depth of the wound at various points (shown in FIG. **14** as z(x,y) where z would be a depth value). In some embodiments, greater disparity may improve the depth calculation, although greater disparity may also result in more computationally intensive algorithms for such depth calculations.

The outputs of both non-linear mapping modules **1310**A, **1310**B are also provided to the linear equations module **1320**, which can treat the sensed values as set of linear equations for spectral unmixing. One implementation can use the Moore-Penrose pseudo-inverse equation as a function of at least sensor quantum efficiency and filter transmittance values to compute actual spectral values (e.g., intensity of light at particular wavelengths that were incident at each (x,y) image point). This can be used in implementations that require high accuracy, such as clinical diagnostics and other biological applications. Application of the spectral unmixing can also provide an estimate of photon flux and SNR.

Based on the disparity-corrected spectral channel images and the spectral unmixing, the workflow **1300** can generate a spectral datacube **1325**, for example in the illustrated format of $F(x,y,\lambda)$ where F represents the intensity of light at a specific (x,y) image location at a specific wavelength or waveband λ.

FIG. **15** graphically depicts disparity and disparity correction for processing image data, for example image data captured using the process of FIG. **13** and/or using the multispectral multi-aperture imaging systems of FIGS. **3**A-**10**B and **12**. The first set of images **1410** show image data of the same physical location on an object as captured by four different sensor regions. As illustrated, this object location is not in the same location across the raw images, based on the (x,y) coordinate frames of the photodiode grids of the image sensor regions. The second set of images **1420** shows that same object location after disparity correction, which is now in the same (x,y) location in the coordinate frame of the registered images. It will be appreciated that such registration may involve cropping certain data from edge regions of the images that do not entirely overlap with one another.

FIG. **16** graphically depicts a workflow **1500** for performing pixel-wise classification on multispectral image data, for example image data captured using the process of FIG. **13**, processed according to FIGS. **14** and **15**, and/or using the multispectral multi-aperture imaging systems of FIGS. **3**A-**10**B and **12**.

At block **1510**, the multispectral multi-aperture imaging system **1513** can capture image data representing physical points **1512** on an object **1511**. In this example, the object **1511** includes tissue of a patient that has a wound. A wound can comprise a burn, a diabetic ulcer (e.g., a diabetic foot ulcer), a non-diabetic ulcer (e.g., pressure ulcers or slow-healing wounds), a chronic ulcer, a post-surgical incision, an amputation site (before or after the amputation procedure), a cancerous lesion, or damaged tissue. Where PPG information is included, the disclosed imaging systems provide a method to assess pathologies involving changes to tissue blood flow and pulse rate including: tissue perfusion; cardiovascular health; wounds such as ulcers; peripheral arterial disease, and respiratory health.

At block **1520**, the data captured by the multispectral multi-aperture imaging system **1513** can be processed into a multispectral datacube **1525** having a number of different wavelengths **1523**, and, optionally, a number of different images at the same wavelength corresponding to different times (PPG data **1522**). For example, the image processor **1120** can be configured by the datacube generation module **1140** to generate the multispectral datacube **1525** according to the workflow **1300**. Some implementations may also associated depth values with various points along the spatial dimensions, as described above.

At block **1530**, the multispectral datacube **1525** can be analyzed as input data **1525** into a machine learning model **1532** to generate a classified mapping **1535** of the imaged tissue. The classified mapping can assign each pixel in the image data (which, after registration, represent specific points on the imaged object **1511**) to a certain tissue classification, or to a certain healing potential score. The different classifications and scores can be represented using visually distinct colors or patterns in the output classified image. Thus, even though a number of images are captured of the object **1511**, the output can be a single image of the object (e.g., a typical RGB image) overlaid with visual representations of pixel-wise classification.

The machine learning model **1532** can be an artificial neural network in some implementations. Artificial neural networks are artificial in the sense that they are computational entities, inspired by biological neural networks but modified for implementation by computing devices. Artificial neural networks are used to model complex relationships between inputs and outputs or to find patterns in data, where the dependency between the inputs and the outputs cannot be easily ascertained. A neural network typically includes an input layer, one or more intermediate ("hidden") layers, and an output layer, with each layer including a number of nodes. The number of nodes can vary between layers. A neural network is considered "deep" when it includes two or more hidden layers. The nodes in each layer connect to some or all nodes in the subsequent layer and the weights of these connections are typically learnt from data during the training process, for example through backpropagation in which the network parameters are tuned to produce expected outputs given corresponding inputs in labeled training data. Thus, an artificial neural network is an adaptive system that is configured to change its structure (e.g., the connection configuration and/or weights) based on information that flows through the network during training, and the weights of the hidden layers can be considered as an encoding of meaningful patterns in the data.

A fully connected neural network is one in which each node in the input layer is connected to each node in the subsequent layer (the first hidden layer), each node in that first hidden layer is connected in turn to each node in the subsequent hidden layer, and so on until each node in the final hidden layer is connected to each node in the output layer.

A CNN is a type of artificial neural network, and like the artificial neural network described above, a CNN is made up of nodes and has learnable weights. However, the layers of a CNN can have nodes arranged in three dimensions: width, height, and depth, corresponding to the 2×2 array of pixel values in each video frame (e.g., the width and height) and to the number of video frames in the sequence (e.g., the depth). The nodes of a layer may only be locally connected to a small region of the width and height layer before it, called a receptive field. The hidden layer weights can take the form of a convolutional filter applied to the receptive field. In some embodiments, the convolutional filters can be two-dimensional, and thus, convolutions with the same filter can be repeated for each frame (or convolved transformation of an image) in the input volume or for designated subset of the frames. In other embodiments, the convolutional filters can be three-dimensional and thus extend through the full depth of nodes of the input volume. The nodes in each convolutional layer of a CNN can share weights such that the convolutional filter of a given layer is replicated across the entire width and height of the input volume (e.g., across an entire frame), reducing the overall number of trainable weights and increasing applicability of the CNN to data sets outside of the training data. Values of a layer may be pooled to reduce the number of computations in a subsequent layer (e.g., values representing certain pixels may be passed forward while others are discarded), and further along the depth of the CNN pool masks may reintroduce any discarded values to return the number of data points to the previous size. A number of layers, optionally with some being fully connected, can be stacked to form the CNN architecture.

During training, an artificial neural network can be exposed to pairs in its training data and can modify its parameters to be able to predict the output of a pair when provided with the input. For example, the training data can include multispectral datacubes (the input) and classified mappings (the expected output) that have been labeled, for example by a clinician who has designated areas of the wound that correspond to certain clinical states, and/or with healing (1) or non-healing (0) labels sometime after initial imaging of the wound when actual healing is known. Other implementations of the machine learning model **1532** can be trained to make other types of predictions, for example the likelihood of a wound healing to a particular percentage area reduction over a specified time period (e.g., at least 50% area reduction within 30 days) or wound states such as, hemostasis, inflammation, proliferation, remodeling or healthy skin categories. Some implementations may also incorporate patient metrics into the input data to further increase classification accuracy, or may segment training data based on patient metrics to train different instances of the machine learning model **1532** for use with other patients having those same patient metrics. Patient metrics can include textual information or medical history or aspects thereof describing characteristics of the patient or the patient's health status, for example the area of a wound, lesion, or ulcer, the BMI of the patient, the diabetic status of the patient, the existence of peripheral vascular disease or chronic inflammation in the patient, the number of other wounds the patient has or has had, whether the patient is or has recently taken immunosuppressant drugs (e.g., chemotherapy) or other drugs that positively or adversely affect wound healing rate, HbA1c, chronic kidney failure stage IV, type II vs type I diabetes, chronic anemia, asthma, drug use, smoking status, diabetic neuropathy, deep vein thrombosis, previous myocardial infarction, transient ischemic attacks, or sleep apnea or any combination thereof. These metrics can be converted into a vector representation through appropriate processing, for example through word-to-vec embeddings, a vector having binary values representing whether the patient does or does not have the patient metric (e.g., does or does not have type I diabetes), or numerical values representing a degree to which the patient has each patient metric.

At block **1540**, the classified mapping **1535** can be output to a user. In this example, the classified mapping **1535** uses a first color **1541** to denote pixels classified according to a first state and uses a second color **1542** to denote pixels classified according to a second state. The classification and resulting classified mapping **1535** may exclude background pixels, for example based on object recognition, background color identification, and/or depth values. As illustrated, some implementations of the multispectral multi-aperture imaging system **1513** can project the classified mapping **1535** back on to the tissue site. This can be particularly beneficial when the classified mapping includes a visual representation of a recommended margin and/or depth of excision.

These methods and systems may provide assistance to clinicians and surgeons in the process of dermal wound management, such as burn excision, amputation level, lesion removal, and wound triage decisions. Alternatives described herein can be used to identify and/or classify the severity of decubitus ulcers, hyperaemia, limb deterioration, Raynaud's Phenomenon, scleroderma, chronic wounds, abrasions, lacerations, hemorrhaging, rupture injuries, punctures, penetrating wounds, skin cancers, such as basal cell carcinoma, squamous cell carcinoma, melanoma, actinic keratosis, or any type of tissue change, wherein the nature and quality of the tissue differs from a normal state. The devices described herein may also be used to monitor healthy tissue, facilitate and improve wound treatment procedures, for example allowing for a faster and more refined approach for determining the margin for debridement, and evaluate the progress of recovery from a wound or disease, especially after a treatment has been applied. In some alternatives described herein, devices are provided that allow for the identification of healthy tissue adjacent to wounded tissue, the determination of an excision margin and/or depth, the monitoring of the recovery process after implantation of a prosthetic, such as a left ventricular assist device, the evaluation of the viability of a tissue graft or regenerative cell implant, or the monitoring of surgical recovery, especially after reconstructive procedures. Moreover, alternatives described herein may be used to evaluate the change in a wound or the generation of healthy tissue after a wound, in particular, after introduction of a therapeutic agent, such as a steroid, hepatocyte growth factor, fibroblast growth factor, an antibiotic, or regenerative cells, such as an isolated or concentrated cell population that comprises stem cells, endothelial cells and/or endothelial precursor cells.

Overview of Example Distributed Computing Environment

FIG. **17** depicts a schematic block diagram of an example distributed computing system **1600** including a multispectral multi-aperture imaging system **1605**, which can be any of the multispectral multi-aperture imaging systems of FIGS. **3**A-**10**B and **12**. As depicted the datacube analysis servers **1615** may include one or more computers, perhaps arranged in a cluster of servers or as a server farm. The memory and processors that make up these computers may be located within one computer or distributed throughout many computers (including computers that are remote from one another).

The multispectral multi-aperture imaging system **1605** can include networking hardware (e.g., a wireless Internet, satellite, Bluetooth, or other transceiver) for communicating over the network **1610** with user devices **1620** and datacube analysis servers **1615**. For example, in some implementations the processor of the multispectral multi-aperture imaging system **1605** may be configured to control image capture, and then send raw data to the datacube analysis servers **1615**. Other implementations of the processor of the multispectral multi-aperture imaging system **1605** may be configured to control image capture and perform spectral unmixing and disparity correction to generate a multispectral datacube, which is then sent to the datacube analysis servers **1615**. Some implementations can perform full processing and analysis locally on the multispectral multi-aperture imaging system **1605**, and may send the multispectral datacube and resulting analysis to the datacube analysis servers **1615** for aggregate analysis and/or use in training or retraining machine learning models. As such, the datacube analysis servers **1615** may provide updated machine learning models to the multispectral multi-aperture imaging system **1605**. The processing load of generating the end result of analyzing the multispectral datacube can be split between the multi-aperture imaging system **1605** and the datacube analysis servers **1615** in various ways, depending upon the processing power of the multi-aperture imaging system **1605**.

The network **1610** can comprise any appropriate network, including an intranet, the Internet, a cellular network, a local area network or any other such network or combination thereof. User devices **1620** can include any network-equipped computing device, for example desktop computers, laptops, smartphones, tablets, e-readers, gaming consoles, and the like. For example, results (e.g., classified images) determined by the multi-aperture imaging system **1605** and the datacube analysis servers **1615** may be sent to designated user devices of patients, doctors, hospital information systems storing electronic patient medical records, and/or centralized health databases (e.g., of the Center for Disease Control) in tissue classification scenarios.

Example Implementation Outcomes

Background: Morbidity and mortality resulting from burns is a major problem for wounded warfighters and their care providers. The incidence of burns among combat casualties has historically been 5-20% with approximately 20% of these casualties requiring complex burn surgery at the US Army Institute of Surgical Research (ISR) burn center or equivalent. Burn surgery requires specialized training and is therefore provided by ISR staff rather than US Military Hospital staff. The limited number of burn specialists leads to high logistical complexity of providing care to burned soldiers. Therefore, a new objective method of pre-operative and intra-operative detection of burn depth could enable a broader pool of medical staff, including non-ISR personnel, to be enlisted in the care of patients with burn wounds sustained in combat. This augmented pool of care providers could then be leveraged to provide more complex burn care further forward in the role of care of warfighters with burn wounds.

In order to begin addressing this need, a novel cart-based imaging device that uses multispectral imaging (MSI) and artificial intelligence (AI) algorithms to aide in the preoperative determination of burn healing potential has been developed. This device acquires images from a wide area of tissue (e.g., 5.9×7.9 in2) in a short amount of time (e.g., within 6, 5, 4, 3, 2, or 1 second(s)) and does not require the injection of imaging contrast agents. This study based in a civilian population shows that the accuracy of this device in determining burn healing potential exceeds clinical judgement by burn experts (e.g., 70-80%).

Methods: Civilian subjects with various burn seventies were imaged within 72 hours of their burn injury and then at several subsequent time points up to 7 days post-burn. True burn severity in each image was determined using either 3-week healing assessments or punch biopsies. The accuracy of the device to identify and differentiate healing and non-healing burn tissue in first, second, and third degree burn injuries was analyzed on a per image pixel basis.

Results: Data were collected from 38 civilian subjects with 58 total burns and 393 images. The AI algorithm achieved 87.5% sensitivity and 90.7% specificity in predicting non-healing burn tissue.

Conclusions: The device and its AI algorithm demonstrated accuracy in determining burn healing potential that exceeds the accuracy of clinical judgement of burn experts. Future work is focused on redesigning the device for portability and evaluating its use in an intra-operative setting. Design changes for portability include reducing the size of the device to a portable system, increasing the field of view, reducing acquisition time to a single snapshot, and evaluating the device for use in an intra-operative setting using a porcine model. These developments have been implemented in a benchtop MSI subsystem that shows equivalency in basic imaging tests.

Additional Illuminants for Image Registration

In various embodiments, one or more additional illuminants may be used in conjunction with any of the embodiments disclosed herein in order to improve the accuracy of image registration. FIG. **21** illustrates an example embodiment of a multi aperture spectral imager **2100** including a projector **2105**. In some embodiments, the projector **2105** or other suitable illuminant may be, for example, one of the illuminants **1165** described with reference to FIG. **12** above. In embodiments including an additional illuminant such as a projector **2105** for registration, the method may further include an additional exposure. The additional illuminant such as the projector **2105** can project, into the field of view of the imager **2100**, one or more points, fringes, grids, random speckle, or any other suitable spatial pattern in a spectral band, multiple spectral bands, or in a broad band, that are individually or cumulatively visible in all cameras of the imager **2100**. For example, the projector **2105** may project light of the shared or common channel, broadband illumination, or cumulatively visible illumination that can be used to confirm the accuracy of the registration of the image calculated based on the aforementioned common band approach. As used herein, "cumulatively visible illumination" refers to a plurality of wavelengths selected such that the pattern is transduced by each of the image sensors in the multi-spectral imaging system. For example, cumulatively visible illumination may include a plurality of wavelengths such that every channel transduces at least one of the plurality of wavelengths, even if none of the plurality of wavelengths is common to all channels. In some embodiments, the type of pattern projected by the projector **2105** may be selected based on the number of apertures in which the pattern will be imaged. For example, if the pattern will be seen by only one aperture, the pattern may preferably by relatively dense (e.g., may have a relatively narrow autocorrelation such as on the order of 1-10 pixels, 20 pixels, less than 50 pixels, less than 100 pixels, etc.), while less dense or less narrowly autocorrelated patterns may be useful where the pattern will be imaged by a plurality of apertures. In some embodiments, the additional exposure that is captured with the projected spatial pattern is included in the calculation of disparity in order to improve the accuracy of the registration compared to embodiments without the exposure captured with a projected spatial pattern. In some embodiments, the additional illuminant projects, into the field of view of the imager, fringes in a spectral band, multiple spectral bands, or in a broad band, that are individually or cumulatively visible in all cameras, such as in the shared or common channel, or broadband illumination which can be used to improve the registration of images based on the phase of fringes. In some embodiments, the additional illuminant projects, into the field of view of the imager, a plurality of unique spatial arrangement of dots, grids, and/or speckle in a spectral band, multiple spectral bands, or in a broad band, that are individually or cumulatively visible in all cameras, such as in the shared or common channel, or broadband illumination which can be used to improve the registration of images. In some embodiments, the method further includes an additional sensor with a single aperture or a plurality of apertures, which can detect the shape of the object or objects in the field of view. For example, the sensor may use LIDAR, light field, or ultrasound techniques, to further improve the accuracy of registration of the images using the aforementioned common band approach. This additional sensor may be a single aperture or a multi-aperture sensor, sensitive to light-field information, or it may be sensitive to other signals, such as ultrasound or pulsed lasers.

Terminology

All of the methods and tasks described herein may be performed and fully automated by a computer system. The computer system may, in some cases, include multiple distinct computers or computing devices (e.g., physical servers, workstations, storage arrays, cloud computing resources, etc.) that communicate and interoperate over a network to perform the described functions. Each such computing device typically includes a processor (or multiple processors) that executes program instructions or modules stored in a memory or other non-transitory computer-readable storage medium or device (e.g., solid state storage devices, disk drives, etc.). The various functions disclosed herein may be embodied in such program instructions, or may be implemented in application-specific circuitry (e.g., ASICs or FPGAs) of the computer system. Where the computer system includes multiple computing devices, these devices may, but need not, be co-located. The results of the disclosed methods and tasks may be persistently stored by transforming physical storage devices, such as solid-state memory chips or magnetic disks, into a different state. In some embodiments, the computer system may be a cloud-based computing system whose processing resources are shared by multiple distinct business entities or other users.

The disclosed processes may begin in response to an event, such as on a predetermined or dynamically determined schedule, on demand when initiated by a user or system administer, or in response to some other event. When the process is initiated, a set of executable program instructions stored on one or more non-transitory computer-readable media (e.g., hard drive, flash memory, removable media, etc.) may be loaded into memory (e.g., RAM) of a server or other computing device. The executable instructions may then be executed by a hardware-based computer processor of the computing device. In some embodiments, the process or portions thereof may be implemented on multiple computing devices and/or multiple processors, serially or in parallel.

Depending on the embodiment, certain acts, events, or functions of any of the processes or algorithms described herein can be performed in a different sequence, can be added, merged, or left out altogether (e.g., not all described operations or events are necessary for the practice of the algorithm). Moreover, in certain embodiments, operations or events can be performed concurrently, e.g., through multi-threaded processing, interrupt processing, or multiple processors or processor cores or on other parallel architectures, rather than sequentially.

The various illustrative logical blocks, modules, routines, and algorithm steps described in connection with the embodiments disclosed herein can be implemented as electronic hardware (e.g., ASICs or FPGA devices), computer software that runs on computer hardware, or combinations of both. Moreover, the various illustrative logical blocks and modules described in connection with the embodiments disclosed herein can be implemented or performed by a machine, such as a processor device, a digital signal processor ("DSP"), an application specific integrated circuit ("ASIC"), a field programmable gate array ("FPGA") or other programmable logic device, discrete gate or transistor logic, discrete hardware components, or any combination thereof designed to perform the functions described herein. A processor device can be a microprocessor, but in the alternative, the processor device can be a controller, microcontroller, or state machine, combinations of the same, or the like. A processor device can include electrical circuitry configured to process computer-executable instructions. In another embodiment, a processor device includes an FPGA or other programmable device that performs logic operations without processing computer-executable instructions. A processor device can also be implemented as a combination of computing devices, e.g., a combination of a DSP and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration. Although described herein primarily with respect to digital technology, a processor device may also include primarily analog components. For example, some or all of the rendering techniques described herein may be implemented in analog circuitry or mixed analog and digital circuitry. A computing environment can include any type of computer system, including, but not limited to, a computer system based on a microprocessor, a mainframe computer, a digital signal processor, a portable computing device, a device controller, or a computational engine within an appliance, to name a few.

The elements of a method, process, routine, or algorithm described in connection with the embodiments disclosed herein can be embodied directly in hardware, in a software module executed by a processor device, or in a combination of the two. A software module can reside in RAM memory, flash memory, ROM memory, EPROM memory, EEPROM memory, registers, hard disk, a removable disk, a CD-ROM, or any other form of a non-transitory computer-readable storage medium. An exemplary storage medium can be coupled to the processor device such that the processor device can read information from, and write information to, the storage medium. In the alternative, the storage medium can be integral to the processor device. The processor device and the storage medium can reside in an ASIC. The ASIC can reside in a user terminal. In the alternative, the processor device and the storage medium can reside as discrete components in a user terminal.

Conditional language used herein, such as, among others, "can," "could," "might," "may," "e.g.," and the like, unless specifically stated otherwise, or otherwise understood within the context as used, is generally intended to convey that certain embodiments include, while other embodiments do not include, certain features, elements or steps. Thus, such conditional language is not generally intended to imply that features, elements or steps are in any way required for one or more embodiments or that one or more embodiments necessarily include logic for deciding, with or without other input or prompting, whether these features, elements or steps are included or are to be performed in any particular embodiment. The terms "comprising," "including," "having," and the like are synonymous and are used inclusively, in an open-ended fashion, and do not exclude additional elements, features, acts, operations, and so forth. Also, the term "or" is used in its inclusive sense (and not in its exclusive sense) so that when used, for example, to connect a list of elements, the term "or" means one, some, or all of the elements in the list.

Disjunctive language such as the phrase "at least one of X, Y, or Z," unless specifically stated otherwise, is otherwise understood with the context as used in general to present that an item, term, etc., may be either X, Y, or Z, or any combination thereof (e.g., X, Y, or Z). Thus, such disjunctive language is not generally intended to, and should not, imply that certain embodiments require at least one of X, at least one of Y, and at least one of Z to each be present.

While the above detailed description has shown, described, and pointed out novel features as applied to various embodiments, it can be understood that various omissions, substitutions, and changes in the form and details of the devices or algorithms illustrated can be made without departing from the scope of the disclosure. As can be recognized, certain embodiments described herein can be embodied within a form that does not provide all of the features and benefits set forth herein, as some features can be used or practiced separately from others. All changes which come within the meaning and range of equivalency of the claims are to be embraced within their scope.

What is claimed is:

1. A multispectral image system, comprising:

at least one image sensor;

a first aperture positioned to allow incoming light to pass to a first sensor region of the at least one image sensor;

a second aperture positioned to allow incoming light to pass to a second sensor region of the at least one image sensor;

a first multi-bandpass filter positioned over the first aperture, wherein the first multi-bandpass filter is configured to allow passage of light in at least a common waveband and a first unique waveband;

a second multi-bandpass filter positioned over the second aperture, wherein the second multi-bandpass filter is configured to allow passage of light in at least the common waveband and a second unique waveband;

a memory storing instructions for generating a multispectral datacube; and

at least one processor configured by the instructions to at least:

receive signals from the first and second sensor regions; and

process the signals to generate the multispectral datacube, wherein the multispectral datacube includes a first spectral channel corresponding to the common waveband, a second spectral channel corresponding to the first unique waveband, and a third spectral channel corresponding to the second unique waveband; wherein processing the signals comprises at least:

estimating, using information from the first spectral channel corresponding to the common waveband, a disparity between first image data captured by the first sensor region and second image data captured by the second sensor region; and

using the disparity to align the image data of the first, second, and third spectral channels to generate the multispectral datacube.

2. The multispectral image system of claim **1**, wherein the at least one processor is configured by the instructions to at least perform spectral unmixing to generate image data for each of the first, second, and third spectral channels.

3. The multispectral image system of claim 1, further comprising at least one light source configured to emit light at the common waveband, the first unique waveband, and the second unique waveband.

4. The multispectral image system of claim 3, further comprising a diffusing optical element positioned over the at least one light source.

5. The multispectral image system of claim 1, wherein at least the first multi-bandpass filter is a curved filter.

6. A method of using the multispectral image system of claim 1 to generate the multispectral datacube, comprising:
capturing a first exposure comprising the first, second, and third spectral channels;
capturing a second exposure comprising the first, second, and third spectral channels; and
generating the multispectral datacube based at least partly on using the second exposure to reduce a signal to noise ratio of the first exposure.

7. The method of claim 6, further comprising registering images captured by the first and second sensor regions to one another based on information in the first spectral channel.

8. The method of claim 7, further comprising generating the multispectral datacube based on a result of registering the images captured by the first and second sensor regions to one another.

9. The method of claim 7, wherein the images represent information captured in the first spectral channel by the first and second sensor regions, the method further comprising:
identifying a disparity between the images captured by the first and second sensor regions in the first spectral channel corresponding to the common waveband;
using the disparity to register a first additional image to the images, the first additional image representing information captured by the first sensor region in the second spectral channel; and
using the disparity to register a second additional image to the images, the second additional image representing information captured by the second sensor region in the third spectral channel.

10. The method of claim 9, wherein each exposure comprises more than three spectral channels, the method further comprising using the disparity to register at least a third additional image to the images, the third additional image representing information captured by a third sensor region in the fourth spectral channel, wherein a total number of additional images registered to the images is one less than the total number of spectral channels.

11. The method of claim 9, further comprising using the disparity to determine at least one of topographic information or depth information.

12. The method of claim 11, wherein the disparity is used to determine depth information for individual pixels.

13. The method of claim 12, further comprising using the depth information to determine a volume of an imaged wound.

14. The method of claim 7, wherein the multispectral image system further comprises an illuminant configured to project one or more points, fringes, grids, random speckle, or other spatial pattern, the method further comprising:
projecting, by the illuminant into a field of view of at least the first aperture, light comprising one or more points, fringes, grids, random speckle, or other spatial pattern; and
capturing an additional exposure using the light projected by the illuminant;
wherein the registering is based at least in part on the additional exposure.

15. The method of claim 14, wherein the light projected by the illuminant comprises at least one of light having a wavelength in the common waveband, broadband illumination, or cumulatively visible illumination.

16. The method of claim 14, wherein the additional exposure is used to confirm an accuracy of the registration.

17. The method of claim 14, wherein the additional exposure is included in a calculation of the disparity to improve an accuracy of the registration.

18. The method of claim 14, wherein the illuminant projects a plurality of points, fringes, grids, speckle, or other spatial patterns in unique configurations in at least the common waveband, broadband illumination, or cumulatively visible illumination.

19. The method of claim 7, wherein the multispectral image system further comprises an additional sensor configured to detect the shape of objects in the field of view of the at least one imaging sensor, and wherein the registering is based at least in part on a shape detected by the additional sensor.

20. The method of claim 7, wherein the illuminant projects the light into a field of view of a plurality of apertures of the multispectral image system.

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